

APPENDIX C

RISK ANALYSIS

Dose Assessment in Support of Decommissioning Plan for Jefferson Proving Ground

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ACRONYMS

ALARA	as low as reasonably achievable
BRAC	Base Realignment and Closure Act
<i>CFR</i>	<i>Code of Federal Regulations</i>
cm	centimeter
CSM	conceptual site model
D&D	decontamination and decommissioning
DGCL	derived concentration guidance level
DOE	U.S. Department of Energy
DU	depleted uranium
ft	foot or feet
FWS	U.S. Fish and Wildlife Service
g	gram
in.	inch or inches
JPG	Jefferson Proving Ground, Indiana
kg	kilogram
L	liter
mrem/y	millirem per year
m	meter
NRC	Nuclear Regulatory Commission
NWR	National Wildlife Refuge
pCi	picocurie
RESRAD	<u>Residual Radioactivity</u>
SBCCOM	Soldier and Biological Chemical Command
TEDE	total effective dose equivalent
U	uranium
USACHPPM	U.S. Army Center for Health Promotion and Preventive Medicine
USDA	U.S. Department of Agriculture
UXO	unexploded ordnance

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1.0 INTRODUCTION

Jefferson Proving Ground (JPG), Indiana, was used by the U.S. Army as one of several locations for testing various munitions used in combat. One of the main activities at JPG was lot-acceptance testing of depleted uranium (DU) penetrator munitions. Testing of DU munitions began about 1984 and was terminated in 1994. JPG was closed under the Base Realignment and Closure Act of 1988 (BRAC) in September 1995. As part of base closure, the U.S. Army was interested in transferring available JPG land to private or public interests, as appropriate. The section of JPG south of the former firing line is being transferred to private/public ownership after extensive removal of hazardous components left over from previous missions. Transfer of lands north of the firing line, however, is not planned because of significant hazards that include not only the DU Impact Area, but also millions of unexploded ordnance (UXO) items that remain. Much of the northern part of JPG has been converted to a managed wildlife area, the Big Oaks National Wildlife Refuge (NWR), which is intended for restricted/limited public use with controlled access.

In this section, the purpose, objectives, scope, and problem definition are discussed. Section 2.0 provides background information on the environmental monitoring program and previous dose assessments. The dose estimation methodology and results are presented in Section 3.0 and provide the basis for conclusions addressed in Section 4.0. References are detailed in Section 5.0.

1.1 PURPOSE AND OBJECTIVES

The U.S. Army is seeking a termination of its radioactive materials license (license number SUB-1435, Amendment 10) and release of the lands for restricted use as defined in 10 *Code of Federal Regulations (CFR)* Part 20, Section 1403. The purpose of this report is to provide an analysis of the potential exposure of site users to DU fragments under a variety of land-use scenarios. The assessment approach and the data used for the assessment area are also documented in this report. Specifically, the following objectives are addressed in this report:

- estimate potential doses from DU fragments in the soil to humans in a critical group as defined by the exposure scenario; and
- evaluate if the expected doses to a member of the appropriate critical group are less than 25 mrem y^{-1} if institutional controls are in place, or the doses are less than 100 mrem y^{-1} if institutional controls fail as stipulated in 10 *CFR* Part 20, Section 1403.

1.2 SCOPE AND PROBLEM DEFINITION

The purpose of the analyses presented in this report is to evaluate potential doses to users of the DU Impact Area after the U.S. Army has released the site for restricted access.

There are two dose limits that govern release of lands for restricted use. First, as long as institutional controls are in place, the total effective dose equivalent (TEDE) to the average member of a critical group cannot exceed 25 mrem y^{-1} and must be kept as low as reasonably achievable (ALARA). The second limit takes effect if institutional controls at the site fail and is a TEDE to the average member of the critical group that is less than 100 mrem y^{-1} , less than 500 mrem y^{-1} if reduction of contamination is technically unachievable, or ALARA. Doses from various scenarios are compared to both limits and are developed below. Termination of the JPG DU license and release of the JPG DU Impact Area for restricted use are recommended if estimated doses are less than the release criteria. Release is not recommended if estimated doses exceed or approach the release criteria.

The main difficulties in estimating the doses to members of critical groups are: (1) the uncertainty in the amount and distribution of DU in the soils at the DU Impact Area; (2) the scarcity of site-specific data required by the dose modeling program; and (3) the need to use default values or estimates for many of the environmental parameters required to run the assessment model. These difficulties are addressed below. The effects of the approximations on the predicted doses also are addressed.

2.0 BACKGROUND: ENVIRONMENTAL MONITORING AND RISK ASSESSMENT AT JPG

In this section environmental monitoring data are reviewed (Section 2.1). Previous dose assessments are summarized in Section 2.2.

2.1 ENVIRONMENTAL MONITORING DATA

An environmental monitoring plan was developed for the JPG DU Impact Area before the initial DU munitions were fired in 1984 (Abbott 1983), and this plan guided sample collection and analysis through 1995. Sampling locations for soils, surface water, and groundwater are shown in the environmental monitoring plan, and the sampling design for vegetation and biota are also presented. Twice each year, samples were collected and analyzed for total uranium (U) and, often, the isotopic composition of U in samples. The environmental sampling data are reported elsewhere (Abbott 1983) and summarized for the 1984–1994 period (Ebinger and Hansen 1996a). Concentrations of DU in soil samples collected in the DU Impact Area from 1984–2000 are skewed left with a mean value of 18.8 picocuries (pCi) g⁻¹ and a median value of 1.5 pCi g⁻¹; the standard deviation of these samples is almost 200 pCi g⁻¹ (Table 1; Figure 1). Of nearly 400 soil samples analyzed since 1984, most total U concentrations are less than 2 pCi g⁻¹, which is no different than the average background soil concentration of U at JPG. Similar distributions for DU concentrations in groundwater and surface water were obtained for the same period (Table 1; Figures 2 and 3). The summary of the environmental data indicates that the expected concentrations of U or DU are significantly less than the derived concentration guideline of 35 pCi g⁻¹ for soil and 150 pCi L⁻¹ for surface water and groundwater developed in an earlier study at JPG (U.S. Army 1996).

Table 1. Descriptive Statistics of DU Concentrations in Soil, Groundwater, and Surface Water Samples Calculated from Environmental Monitoring Samples Collected 1984 through 2000

	Soil (pCi g ⁻¹)	Groundwater (pCi L ⁻¹)	Surface Water (pCi L ⁻¹)
Mean	18.8	2.7	1.6
Median	1.5	1.3	0.26
Standard Deviation	197.1	5.6	5.6
Minimum	-0.8	-0.1	-1.2
Maximum	3857	81.1	49
Number of Samples	388	365	312

Source: Ebinger and Hansen 1996a.

g = gram.

pCi = picocurie.

L = liter.

The hydrology of JPG lands south of the firing line was evaluated during remediation efforts associated with BRAC and land transfer by the Army (Rust 1994, 1998). The groundwater hydrology at JPG is complicated because of the karst terrain, but the overall flow was thought to be generally from northeast to the southwest and parallel to the flow of streams that cross the DU area, namely Big Creek.

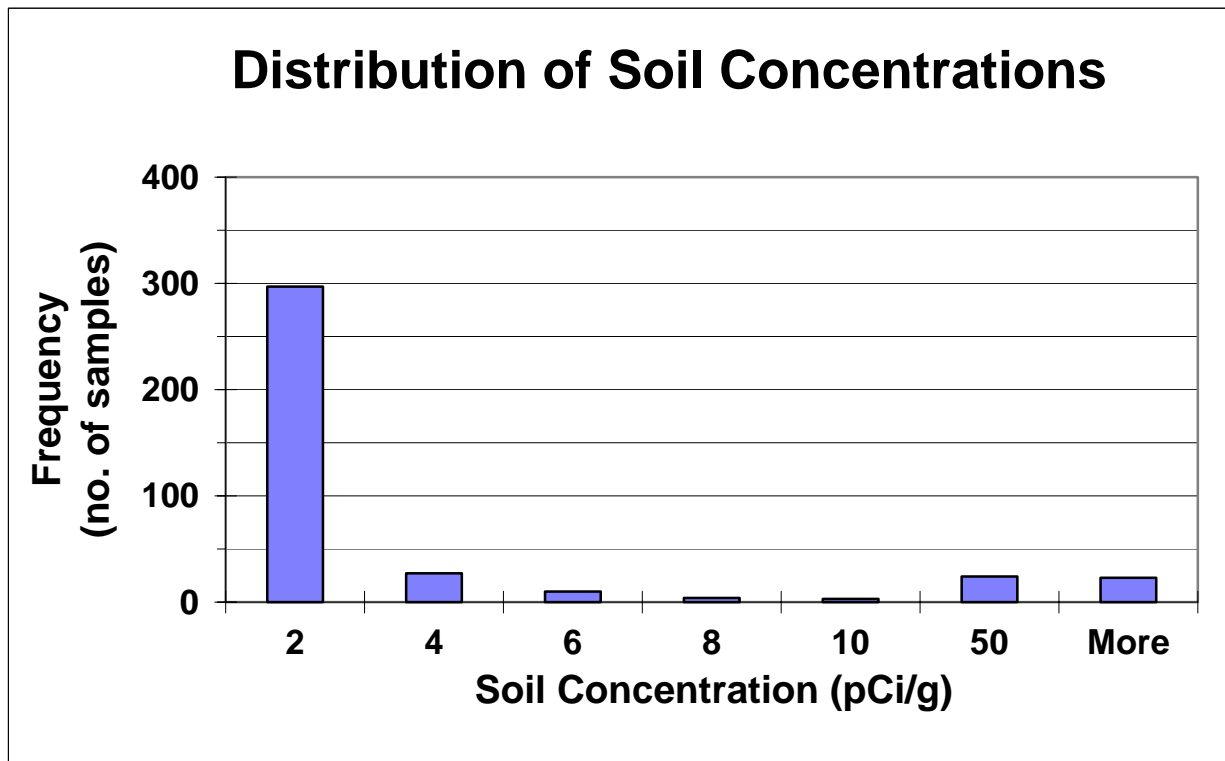


Figure 1. Frequency Distribution of Soil Samples Collected from 1984 through 2000
 “More” refers to samples with concentrations greater than 50 pCi/g (Ebinger and Hansen 1996a).

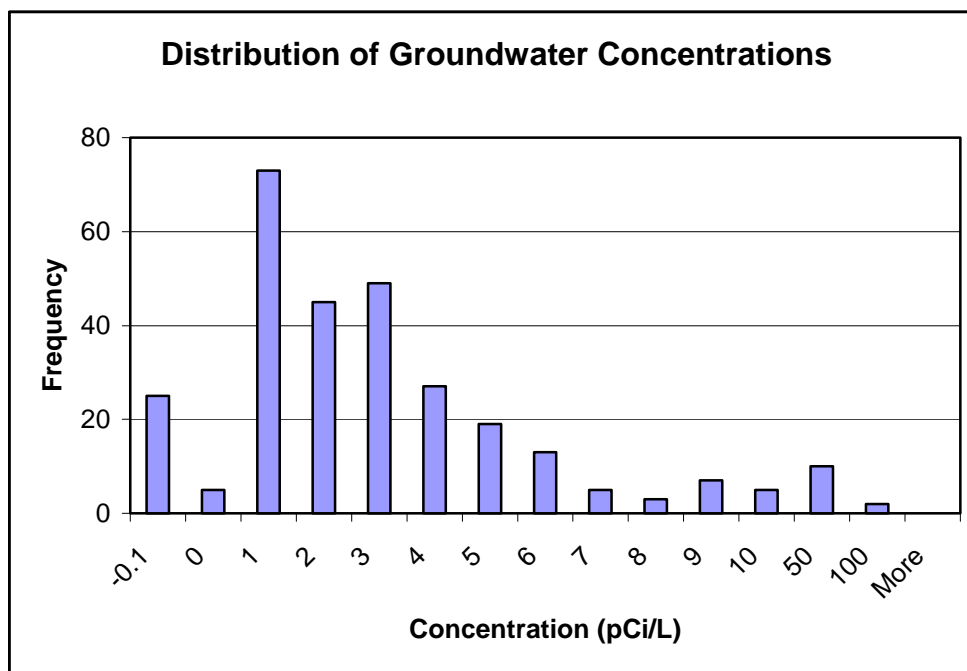


Figure 2. Frequency Distribution of Groundwater Samples Collected from 1984 through 2000 (Ebinger and Hansen 1996a)

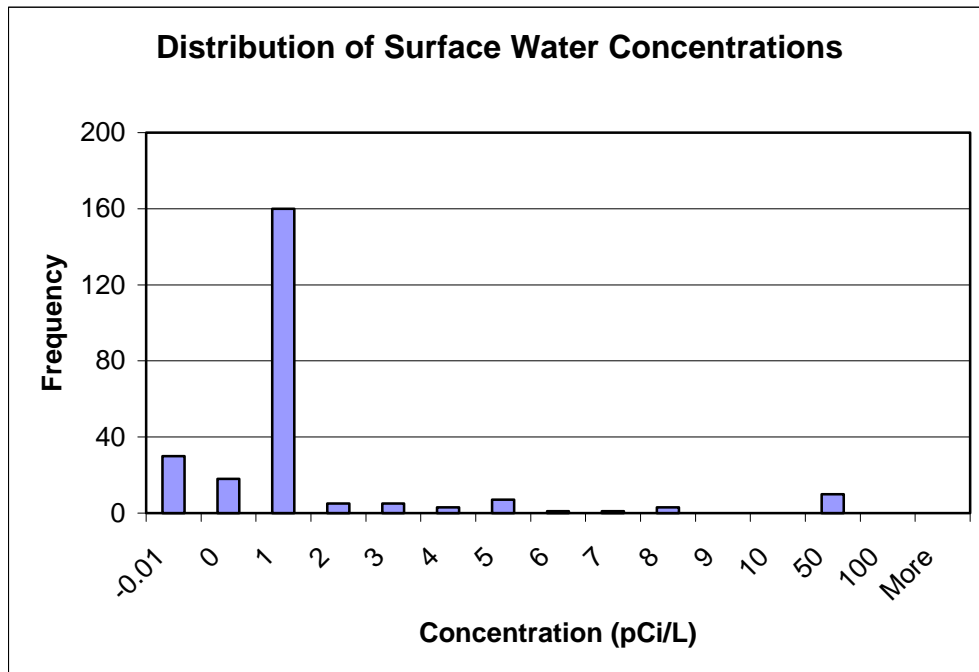


Figure 3. Frequency Distribution of Surface Water Samples Collected from 1984 through 2000 (Ebinger and Hansen 1996a)

Establishing the regional hydrology was not within the scope of the Rust reports, nor was characterization of the deeper groundwater hydrology at the site. Therefore, detailed descriptions of the overall hydrologic setting cannot be made at this time.

Several monitoring wells were completed around the DU firing range between 1984 and 1994. These wells were bored to various depths that ranged to over 40 feet (ft) from the surface [well logs, personal communication with Richard Herring, JPG, retired; personal communication with Soldier and Biological Chemical Command (SBCCOM) and U.S. Army Center for Health Promotion and Preventive Medicine (USACHPPM) staff, Aberdeen Proving Ground; and SEC Donohue 1992]. The groundwater data show some variation in the concentration of U in wells between 1984 and 2000 (Figure 2), the largest of which was attributed to error in sample handling at the analytical laboratories (Ebinger and Hansen 1996a). Overall, the data indicate that no DU contamination has moved to the groundwater or surface water from the DU Impact Area. This conclusion was further supported by the isotopic composition of U in the groundwater samples (Ebinger and Hansen 1996a).

Surface water samples from monitoring locations on Big Creek upstream and downstream from the DU Impact Area varied in U and DU concentration during the 1984–2000 period, but there was neither long-term elevation of the concentration, nor sustained, elevated concentration at any sampling site. Some of the observed variation in surface water samples could be due to U incidentally applied as a trace constituent of phosphate fertilizer used throughout the farming community that surrounds JPG (Klement 1980; Eisenbud 1987). Isotopic ratios of these samples support that most of the observed variation was due to a natural U in surface water and not DU. The summary data suggest that the main source of U in surface waters has been natural in origin, that is, from fertilizers or derived from geologic deposits, and transported via water or erosion. Whether from natural sources or agricultural fertilizer, the concentrations are well below the Army derived concentration guidance levels (DGCLs) [U.S. Army 1996] and low enough to be of little concern.

2.2 PREVIOUS DOSE ASSESSMENTS

Several dose estimates for the potential effects of DU on members of appropriate critical groups have been conducted at JPG (Ebinger and Hansen 1994, 1996a,b, and 1998), and the predicted doses depended largely on the assumptions made about exposure pathways. In the earliest assessments, it was demonstrated that drinking water was the largest contributor to the overall dose to humans. Since the first estimates were completed, however, refinements have been made concerning DU transport to groundwater and surface water, and more realistic exposure scenarios have been developed. The most recent assessment assumed that the soil and geologic media that control groundwater recharge and DU transport were characterized well enough to use as modeling scenarios. This assumption is optimistic given that the hydrologic data (Rust 1994, 1998) were obtained from an area about 5 miles southwest of the DU Impact Area and may not be completely relevant to the hydrology of the DU Impact Area. The approach adopted for this report is to model the transport of DU at JPG relying on site-specific data as much as possible.

Refinements in the distribution and concentration of DU in the DU Impact Area were made in 1995 and 1996 (SEG 1995, 1996). These reports show that the size of the affected area could be more reliably estimated after radiological surveys were completed along a grid through the DU Impact Area. These survey data were used to map exposure rates at the surface of the soil, and for contaminated area delineation. However, the data were difficult to use to estimate source term concentrations because they were radiation rate measurements from all radionuclides present at the surface of the soil, not actual DU concentrations. The source terms for DU are the result of a refined estimate of the affected area from the SEG (1995, 1996) data and use of maximum and average concentration estimates from survey data.

3.0 DOSE ESTIMATION METHODOLOGY

The dose estimation methodology is described in Sections 3.1 to 3.9. The RESRAD results are detailed in Section 3.10. This section concludes with a discussion on the effects of uncertainty in parameter values (Section 3.11).

3.1 INTRODUCTION

Termination of the U.S. Army radioactive materials license (SUB-1435, Amendment 10) and release of the DU Impact Area for restricted use depends on demonstrating that estimated radiological doses to humans using the lands are less than 25 mrem y^{-1} if institutional controls remain in place or less than 100 mrem y^{-1} if institutional controls fail as set forth in 10 *CFR* Part 20, Section 1403. In order to estimate potential doses from residual DU at JPG, the following dose assessment methodology was designed. First, a conceptual site model (CSM) was developed that included potential exposure from a variety of environmental pathways. These pathways included DU contaminated soil, drinking water and irrigation water supplies potentially contaminated by DU leaching from the soils, DU transferred to the food chain via plant and animal (livestock, fish, and poultry) consumption, and transfer of DU via inhaled dust and soil ingestion. A set of exposure scenarios was developed according to the CSM. The exposure scenarios included various land uses, and the potential for exposure to DU via environmental pathways relevant to those land uses was evaluated. Exposures for on-site and off-site receptors were evaluated using the CSM and appropriate environmental pathways.

Next, the magnitude of the source term was estimated. Historical information of the amount of DU fired at JPG was used to estimate the upper bound of the total DU that remains in the DU Impact Area, and data from environmental sampling was used to refine the distribution of DU and the concentrations that

characterize the affected area. The area considered affected by residual DU fragments is defined as the contaminated zone for dose assessment modeling and was delineated using radiological characterization surveys conducted after DU firing missions at JPG ceased. Two different contaminated zones with two associated DU concentrations were derived and serve as separate source terms.

Exposures were estimated for the average member of critical groups relevant to each tested scenario. Since the critical groups were different for the various scenarios, a separate critical group was identified for each. Thus, critical groups for on-site and off-site exposures, as well as exposures that varied with each scenario, were identified.

Next, the set of scenarios was screened to reduce the amount of repetition in dose estimate calculations. The scenarios selected for simulation represent a range of potential exposures from incidental doses by occasional site users to doses expected from a farming operation located in the contaminated zone. The tested scenarios were meant to be as realistic as possible; however, intense land uses, such as farming, omitted the potential injury or death of farmers from encounters with UXO.

Finally, the selected scenarios were used to formulate dose estimates using the U.S. Department of Energy (DOE) Residual Radiation (RESRAD) program (Yu et al. 2001), and site-specific data were included in the model simulations. The sensitivity of the RESRAD simulations was evaluated to variation in input parameters, and the uncertainty of the predicted doses was estimated using probabilistic information for the sensitive parameters. The resulting dose estimates were used to evaluate if the JPG DU Impact Area could be released for restricted use within the stipulations of 10 *CFR* Part 20, Section 1403.

3.2 DEFINITIONS: “ON-SITE,” “OFF-SITE,” “CONTAMINATED ZONE,” AND “DU IMPACT AREA”

Four terms used in the dose estimation assessments below refer to specific sections of the JPG area. The area under institutional control is that area north of the former firing line and enclosed by the current JPG boundary on the north, east, and west with a 7-foot (2.1 m) high chain link fence topped with V-shaped three-strand barbed wire (Figure 4). The DU Impact Area lies within the area under institutional control and has been marked with radiation contamination signs and secured by a locked swing gates on all access roads to the area. The area south of the firing line does not contain DU test areas. Contaminants from portions of this area are being removed, and transfer to the public or local businesses is under way or scheduled. In the following descriptions of the potential exposure scenarios, “on-site” refers to being within the area under institutional control, “off-site” refers to areas outside the institutional control fence, and “DU Impact Area” refers to the area within the northern part of JPG where DU munitions impacted the ground, and the “contaminated zone” is the area of highest concentration of DU from within the DU Impact Area (Figure 4). Appropriate interpretation of the conclusions of the exposure modeling effort below depends on these definitions.

3.3 JPG CONCEPTUAL MODEL

A site description is provided in Section 3.3.1. This discussion is followed by a presentation of the conceptual site model (Section 3.3.2).

3.3.1 Site Description

The area enclosed by JPG is considered ideal farming land because of the favorable temperature during the growing season, a relatively long growing season, and adequate moisture to grow a variety of crops without added irrigation and without danger, in most years, of crop loss from drought [U.S. Department

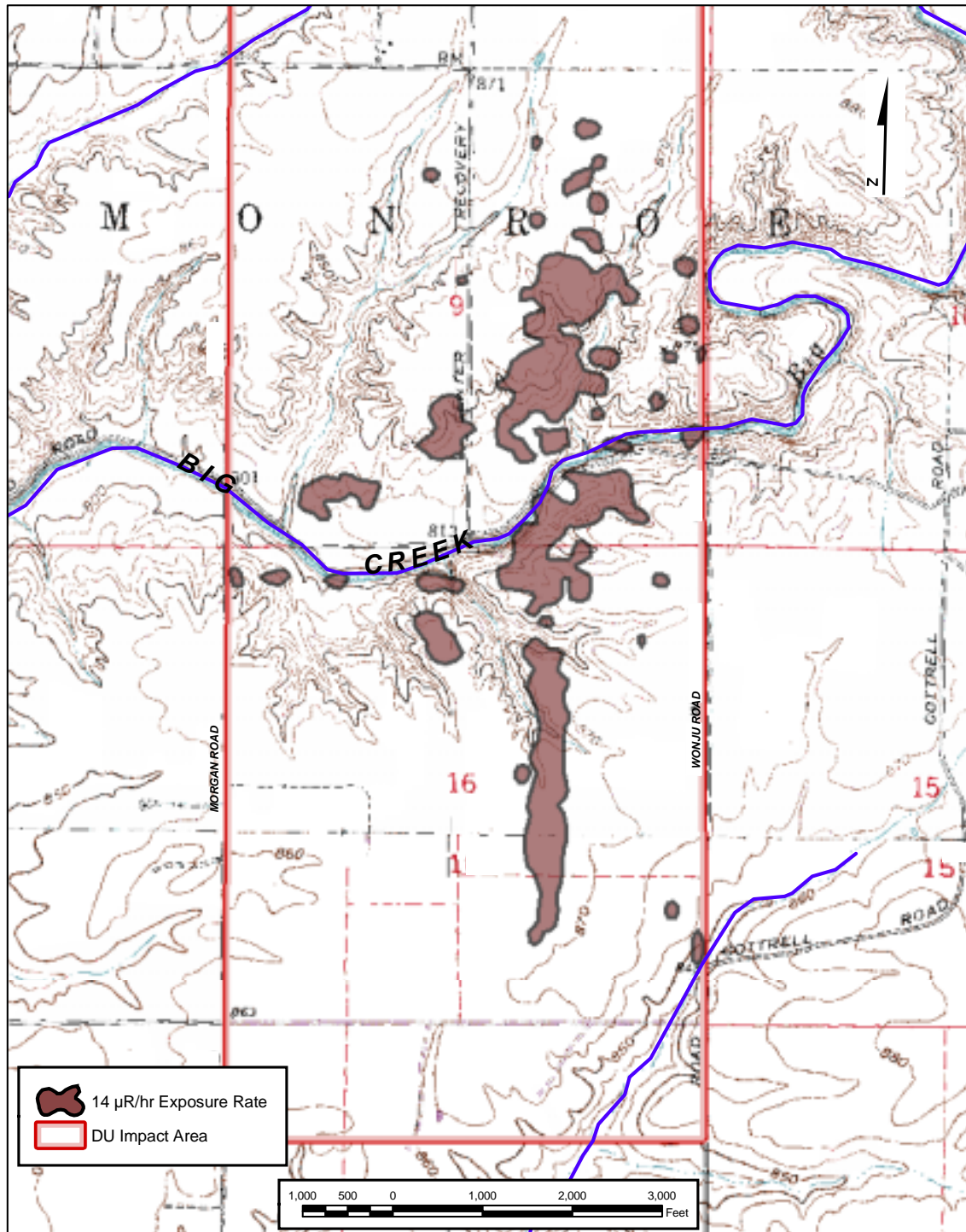


Figure 4. Map Showing the DU Impact Area and Two Areas Used as the Contaminated Zone for RESRAD Simulations

(The DU Impact Area lies within the red boundaries; the contaminated zone of $1.2 \times 10^6 \text{ m}^2$ lies within the polygon outlined by the black lines; and the contaminated zone of $5 \times 10^5 \text{ m}^2$ is the sum of the area within the irregular gray shapes. The scale bar on the bottom of the map is 1000 ft.)

of Agriculture (USDA) 1997]. Adequate surface and groundwater resources ensure a regular water supply, including the Ohio River, which flows within 20 km (10 miles) of the south boundary of JPG. The JPG area is now forested with various hardwoods, herbaceous cover, and grasses, and supports a large population of game animals, non-game mammals, aquatic life, and reptiles. Between the late 1800s and 1943, JPG lands were cleared of timber and farmed extensively, but returned to a forest ecosystem after the U.S. Government took control of the area in World War II. The JPG reservation is cut from east to west by several rivers, notably Big Creek that flows through the DU Impact Area. Trenches were carved from south to north by munitions impacts that removed trees. The trenches or firing lines are enclosed within the DU Impact Area.

Soils of the area are derived mainly from glacial till covered by up to one meter (m) of loess (Nickell 1985). Strongly indurated horizons or fragipans can form as a result of the combination of loess over till and the annual precipitation of 1 m [40 inches (in.)] or more. Low permeability and conductivity of fragipans restrict water movement through these horizons, and ponding is a common occurrence in wet seasons on the site. The major soil series of the DU Impact Area at JPG is Cobbsfork silt loam (fine-silty, mixed, mesic Typic Ochraqualf), located on nearly flat plains with co-occurrence of Cincinnati silt loam, Avonburg silt loam, Grayford silt loam, and Ryker silt loam as the slope of the landscape becomes steeper (Nickell 1985). The Cobbsfork series poses only slight erosion hazard due to the mainly flat slope, and is good for pond construction due to the relatively low permeability of the fragipans. However, Cobbsfork silt loam is severely limited for septic applications and building sites because of the poor drainage, and these soils are difficult to develop for recreational purposes for the same reason (Nickell 1985). These soils are at least a meter deep on average, and unsaturated subsoils extend to a maximum of 6 to 7 m in depth in some cases. Shallow bedrock formations include limestone with interbeds of pyritic shale, and these are commonly observed in stream sediments, bank cuts, and road cuts in and around JPG. Water movement into and through the soil and deeper geologic media is assumed to be parallel to the flow of the main streams (e.g., Big Creek). Detailed hydrologic studies have not been conducted, but previous work showed that subsurface water flow is in the direction of the streams (Rust 1994, 1998). Soil properties important for dose estimation are discussed below.

3.3.2 Conceptual Site Model

As indicated above, JPG is undergoing reforestation after approximately 50 years of intense agriculture. The maturing woodland supports a variety of terrestrial and aquatic wildlife, and previous munitions testing at JPG has clearly resulted in deposition of large amounts of DU fragments. Exposure to DU of the many resources within the DU Impact Area can occur by several pathways. Figure 5 is a summary of the processes that control DU transport and migration at JPG and a list of potential exposure pathways.

In principal, DU transports and migrates by a variety of processes after deposition in soil (Figure 5). DU can dissolve within the soil and leach to groundwater; the dissolved DU can react with soil minerals that slow its transport to groundwater; and soluble DU can be taken up by plant roots and incorporated into various plants. Since plants grow in the soils that are contaminated, ingestion of plants by animals necessarily includes incidental ingestion of DU-contaminated soil. In addition, soils are also susceptible to wind and water erosion and transport (Whicker et al. 2002); thus, DU could be transported through the air or moved into surface waters by various erosion processes, and Williams et al. (1998) discuss transport of contaminants by smoke from fires. Finally, DU may transport with groundwater to drinking water supplies, or be used as well-derived irrigation water. Irrigation water is, thus, a mechanism by which some of the transported DU is recycled to the soil as well as a source for DU to plants that are irrigated. Doses to humans and ecosystem receptors can come from any number of exposure pathways beginning when the munitions are tested and lasting until DU is removed from the system. Thus, the dose to humans from DU must be assessed for a variety of pathways, and for a relatively long time due to slow transport through soils.

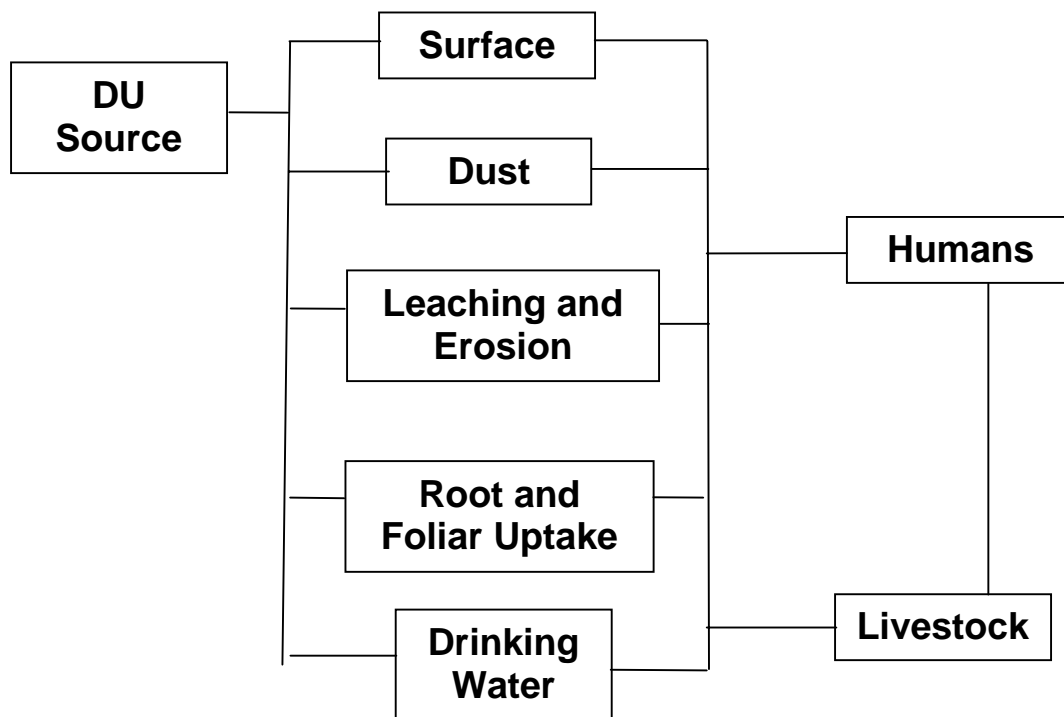


Figure 5. Conceptual Model of DU Transport Through Environmental Compartments to Humans (after Yu et al. 2001)

3.4 SOURCE TERM CHARACTERIZATION

Source term characterization is addressed in this section. Section 3.4.1 to 3.4.3 present the contaminated zone, DU soil concentrations, and the source term for off site exposure estimates, respectively.

3.4.1 Contaminated Zone Delineation

The source term for RESRAD simulations is assumed to be located in a specific area within a given depth of soil and is of uniform concentration throughout the area. For JPG, the contaminated zone is the area within the DU Impact Area (Figure 4) that contains DU concentrations greater than background concentrations as defined by scoping and characterization survey data (SEG 1995, 1996a,b). The DU Impact Area is located in the south-central part of the JPG reservation north of the firing line and covers approximately 2,080 acres (8.4 km²)(Figure 4). The scoping and characterization survey data indicate that the actual area contaminated by DU fragments is considerably smaller than the entire impact area. Field observations throughout the period of 1984 through 1999 also indicate that DU contamination is restricted mainly to the main firing corridors and areas surrounding the trenches that formed on the main firing lines as a result of DU testing. Two estimates of the contaminated zone were derived from the characterization survey data (SEG 1995, 1996a) and range from 5×10^5 m² to 1.2×10^6 m². The smaller area, 5×10^5 m², was based on radiation survey data from a grid of sampling points within the DU Impact Area. Most of the survey measurements were not significantly different from uncontaminated areas, but about 5 percent (%) of the samples exceeded $13.3 \mu\text{R hr}^{-1}$ and were assumed to be the result of residual radiation from DU fragments. In addition to the survey measurements and the determination that 95% of the area surveyed was less than the $13.3 \mu\text{R hr}^{-1}$ value, a guideline of 35 pCi g⁻¹ of soil was used to delineate the

contaminated zone. This value was established as a guideline in the JPG license agreement and is based on a 1961 Nuclear Regulatory Commission (NRC) Notice (*Federal Register* Vol. 48, No. 25, Oct. 23, 1961). The guideline value corresponds to approximately $14.4 \mu\text{R hr}^{-1}$ (SEG 1996a); thus, the $13.3 \mu\text{R hr}^{-1}$ estimate for the area contaminated by DU fragments includes those areas that would also exceed 35 pCi g^{-1} for remediation purposes. The area greater than $13.3 \mu\text{R hr}^{-1}$ criterion is approximately $5 \times 10^5 \text{ m}^2$ (SEG 1996a). For the purposes of the RESRAD simulations, this contaminated zone is described by a polygon that extends about 1,000 m north to south and 500 m east to west (Figure 4). This rectangle eliminates some of the areas that are less than $13.3 \mu\text{R hr}^{-1}$ and may be unrealistically shaped for the RESRAD simulations. The result of using this size and shape for the contaminated zone, though, should over-estimate the potential exposure to humans by increasing the average soil concentration throughout the contaminated zone. This contaminated area falls mainly along the firing corridors as shown by SEG maps (Figure 4; SEG 1996a, Figure 5-2).

The SEG surveys (SEG 1996a) indicate that areas with measured rates less than $13.3 \mu\text{R hr}^{-1}$ separated those areas along the firing corridors that exceeded the $13.3 \mu\text{R hr}^{-1}$ criterion. Thus, a more realistic contaminated area was estimated by including these areas and increasing the size of the polygon that describes the contaminated zone (Figure 4). Because of this, an upper bound of $1.2 \times 10^6 \text{ m}^2$ was estimated for the contaminated zone. Each of the contaminated zone areas was incorporated into the RESRAD simulations to provide exposure estimates under a range of realistic initial conditions.

3.4.2 DU Concentration in Soil

The average concentration of DU fragments in the soil was estimated from (1) environmental monitoring data collected between 1984 and 1995; (2) data collected during the 1995 and 1996 surveys (SEG 1995, 1996a); and (3) by assuming an inventory of 70,000 kilograms (kg) of DU fragments remains in the impact area after the testing program was completed and JPG was closed. The latter estimate of DU inventory was derived from accounts of the amount of DU fired at the site adjusted for DU fragments that were collected and disposed of before base closure occurred in 1995. Based on these data and the analyses conducted by SEG (1995, 1996a), the soil concentrations of DU within the contaminated zone are bounded by 94 pCi g^{-1} from a contaminated zone of $1.2 \times 10^6 \text{ m}^2$ to 225 pCi g^{-1} from a contaminated zone of $5 \times 10^5 \text{ m}^2$ (Table 2).

Table 2. Estimated Areas of the Contaminated Zone and Corresponding Average Concentrations of DU in Soil

Area of Contaminated Zone (m^2)	Average Soil Concentration (pCi g^{-1})
5×10^5	225
1.2×10^6	94
2.8×10^6	40

Note: Average soil concentration assumes an inventory of 70,000 kg of depleted uranium is uniformly distributed in the top 15 centimeters of the soil.

g = gram.

m^2 = square meters.

pCi = picocurie.

The 70,000-kg inventory is the upper limit of soil concentrations of DU for the RESRAD simulations. Using this inventory, a fixed depth of the contaminated zone soil, and a specific soil bulk density, the area of the contaminated zone can be calculated. Use of this approach, however, may not account for the actual distribution of DU fragments along the firing lines and the variation of soil bulk density and other soil properties across a site. Using a bulk density of 1.6 grams per cubic centimeter (g/cm^3) and depth of 15 centimeters (cm), a range of contaminated zone areas could be calculated for a variety of soil

concentrations. The relationship between the size of the contaminated zone and average soil concentration is shown in Table 3.

Table 3. Effect of Average Soil Concentration on Size of the Contaminated Zone for RESRAD Simulation

Average Concentration (pCi g ⁻¹)	Contaminated Zone Area (m ²)
10	1.1×10^7
20	5.6×10^6
35	3.2×10^6
100	1.1×10^6
240	4.7×10^5

Note: The contaminated zone area is determined by (1) total DU inventory of 70,000 kg remaining in the impact area and (2) a contaminated zone that is 15 cm thick.

g = gram.

m² = square meters.

pCi = picocurie.

The depth of the contaminated zone has been difficult to establish, but two estimates support a depth of 15 cm. Previous data of DU concentrations with depth from Aberdeen Proving Ground and Yuma Proving Ground (Ebinger et al. 1995) show that DU was detected to about 20 cm, and at 20 cm the concentrations were nearly at background levels. In a separate analysis of DU activity with depth, SEG (1996a) showed that the 35 pCi g⁻¹ concentration was achieved if approximately 11 cm of contaminated soil were removed from the contaminated area. Additional analysis of the DU concentrations in soil under penetrators lying on the surface indicates that 97% of the total DU in the top 60 cm of the soil is found between the surface and 15 cm depth (Table 4). Data from random locations within the DU Impact Area indicate that little, if any, DU is detected outside the firing corridor at any depth, and the concentration of the U that is detected at these locations does not vary significantly with depth (Table 5). It is noted, though, that DU concentrations in some locations are at least greater than the detection limit, and this information supports the idea that a fraction of the deposited DU fragments leach into the soils (SEG 1996a). Also, penetrator fragments at depths below 45 cm have been observed and result from deep impacts within the DU Impact Area. These occurrences, however, are the exception to what is usually observed in the field and in the data from soil samples. Thus, from the analyses of DU concentration data, the 15 cm depth appears to contain most of the DU deposited during testing at JPG and was selected as the contaminated zone depth for these tests.

Table 4. DU Concentrations in Soil Beneath Penetrators on the Surface

Sampled Depth (cm)	Average Concentration (pCi g ⁻¹)	Minimum Value (pCi g ⁻¹)	Maximum Value (pCi g ⁻¹)	Standard Deviation (pCi g ⁻¹)	Percent of Total DU
0 to 15	2,881	2.9	12,318	3,470	96.7
15 to 30	79.5	1.5	547	131	2.7
30 to 45	12.7	1.8	63	16.4	0.4
45 to 60	4.6	1.4	11.5	3.4	0.2

Note: See SEG 1996a for raw data.

cm = centimeter.

DU = depleted uranium.

g = gram.

pCi = picocurie.

Table 5. DU Concentrations in Soil at Random Locations Within the DU Impact Area

Sampled Depth (cm)	Average Concentration (pCi g⁻¹)	Minimum Value (pCi g⁻¹)	Maximum Value (pCi g⁻¹)	Standard Deviation (pCi g⁻¹)
0 to 15	2.6	1.46	4.73	0.9
15 to 30	2.4	1.51	6.94	1.21
30 to 45	2.0	1.34	4.21	0.68

Note: See SEG 1996a for raw data.

cm = centimeter.

DU = depleted uranium.

g = gram.

pCi = picocurie.

3.4.3 Source Term for Off-Site Exposure Estimates

A modified source term also is needed for estimation of doses associated with off-site exposures. The initial source term, as defined above, was used, and transport of this source material via wind, surface water (i.e., sediment deposition during flooding), and groundwater to off-site locations was considered the source term for off-site exposures. Sediment eroded from the contaminated zone can be transported by surface water (e.g., Big Creek) and deposited downstream. Simulation of sediment transport during floods was conducted in order to evaluate the magnitude of this process and integrate the results into dose assessments of off-site receptors. Attachment 1 is the flood analysis and sediment yield estimates for the western boundary of JPG. Concentrations of uranium in Big Creek water were estimated using surface water flow rates and erosion rates estimated in the flood analysis. Contamination of off-site soil was assumed to occur via use of water from Big Creek for irrigation.

3.5 ENVIRONMENTAL PATHWAYS

The CSM (Figure 4) shows the processes that control DU transport and migration from soil to groundwater, surface water, and different biotic receptors. Figure 6 identifies specific environmental pathways from DU source to humans. Exposure can occur through external radiation of humans; inhalation of airborne, DU-containing dust; and/or ingestion of DU via the human food chain or drinking water.

Direct exposure results from radiation received via DU fragments in the soil as the uranium isotopes and daughter products decay to stable isotopes (Shelien 1992). Much of the radiation is absorbed by soil minerals, soil water, and within the media through which the decay products travel. The small fraction of radiation that reaches human receptors can be absorbed by the skin and results in external doses to humans. Inhalation of DU can occur when DU-containing soil is lifted from the soil surface and remains airborne long enough to enter the lungs of a receptor. For this environmental pathway to be effective, the receptors must be close enough to the contaminated zone during the time when DU-containing dust is airborne. Also, the dose is proportional to the distance from the source so more dose is expected from on-site exposure than from off-site. Both external exposure and exposure from inhalation affect on-site and off-site receptors. However, since both depend on the time spent at the source area and the distance from the source area, on-site receptors will be more affected than off-site receptors by this pathway.

Ingestion of DU can occur through a variety of environmental pathways (Figure 6). Uptake by plants through roots and foliar deposition are the main mechanisms of transfer to plant material. Contaminated plants can be fed to livestock as fodder; contaminated beef, poultry, or dairy products could then be consumed by humans. Also, contaminated plants, such as vegetables from a summer garden or a subsistence farm, can be directly consumed by humans. Thus, the DU source-plant-livestock-human and

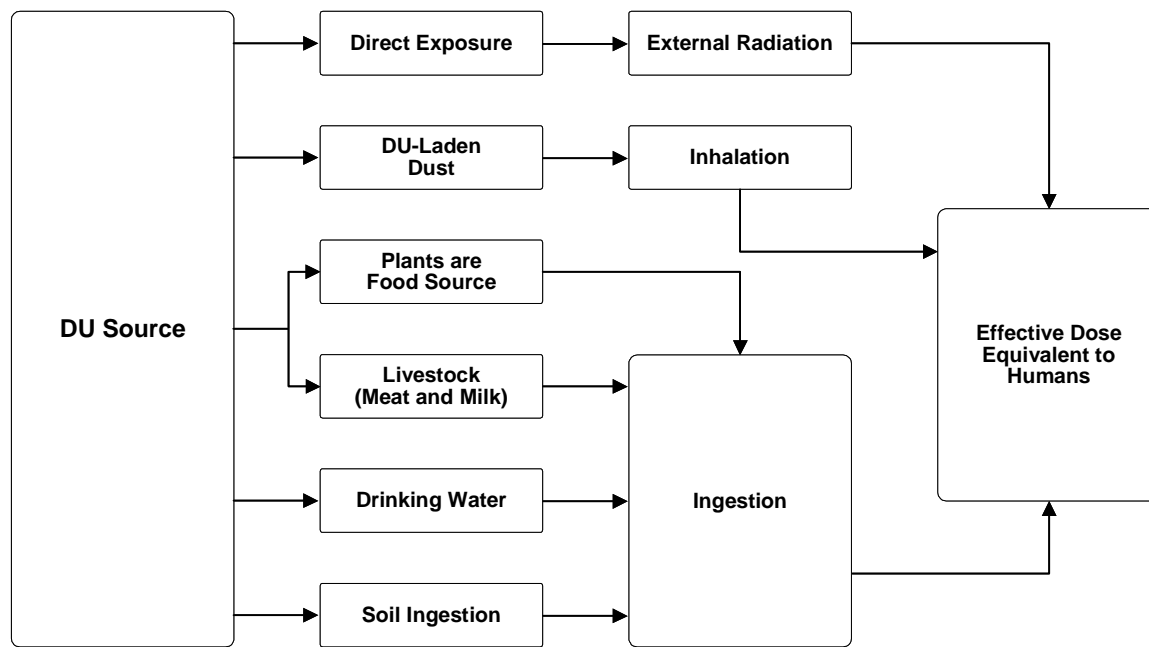


Figure 6. Schematic Diagram of RESRAD Program Illustrating Environmental Pathways of Exposures

DU source-plant-human pathways are important to consider in risk estimates. These pathways are particularly important to the farming and domestic scenario described below.

Soil ingestion can also be a significant environmental pathway with regard to dose estimates. Humans can be exposed by this pathway directly by incidental ingestion of DU-containing soil on vegetables or other food products that contact contaminated soil. Indirectly, contaminated soil can be ingested by livestock and passed to humans via poultry, beef, and dairy product consumption. Because of the potentially large contribution to total dose from direct and indirect soil ingestion, these pathways are modeled below.

Contamination of drinking water by DU leaching through soil to aquifers is an environmental pathway that could affect humans off-site and on-site for considerable periods. DU transport by physical means, such as erosion of soils and deposition away from the contaminated zone by streams, is a pathway considered. Also considered is dissolution of DU from fragments and transport via soil water to aquifers used for irrigation, drinking water, or both. Effects of this pathway could show up early in the dose estimations or many years in the future depending on the hydrologic characteristics of the soils of the contaminated zone and underlying geology. The effects of the contaminated groundwater pathways include ingestion of water by livestock, then passing the DU to humans through beef, poultry, and dairy products. A second effect is the direct exposure of humans through drinking water. Both types of environmental pathways are included in the dose modeling below. While the drinking water pathway is included in the dose modeling, the quality of water from shallow groundwater wells was not considered. Some data (Rust 1994, 1998) indicate that the quality of water is below drinking water standards because of sediment or other contaminants not related to DU, and these low-quality waters occur at the depths included in the modeling. Low-quality water would mean that deeper wells are required, and this would also decrease the amount of DU in drinking water and decrease the potential dose to receptors at JPG.

Surface water can also be contaminated by DU transported by water erosion as well as contaminated groundwater flowing into ponds or streams that are used by humans. Contaminated surface water can enter the human food chain indirectly as livestock drinking water or directly through the drinking water supply as discussed above for groundwater. In addition, fish raised in ponds that contain contaminated water represent an additional pathway to humans. The DU-surface water-fish-human pathway is included in the dose modeling presented below.

Environmental pathways for on-site and off-site receptors differ mainly in the source term used for the calculations. On-site receptors are assumed to be in proximity to the contaminated zone, either occasionally as hikers, hunters, or fisherman, or daily as resident farmers. Off-site receptors are exposed to similar environmental pathways as on-site receptors, but because the source term has been reduced by transport processes (Figures 4 and 5), the magnitude of the expected doses will be proportionally less. Thus, the amount of DU contamination in the external, inhalation, and ingestion pathways would be considerably less than the same pathways for on-site exposure. Because of the contact with the contaminated zone, via multiple pathways in some of the scenarios, the potential exposure of on-site receptors would be greater than exposure of off-site receptors.

3.6 CRITICAL GROUPS

The various human receptors mentioned above depend on exposure of the average member of the hypothetical critical group. For this report, the critical group is defined as a group of individuals that is expected to receive the largest exposure to DU within the DU Impact Area. The average member of that group is a person expected to receive the dose from an ordinary use of the site based on the exposure scenario. Since each scenario developed is different and the critical group for a particular scenario varies accordingly, a more specific average member of the critical group is given in the scenario descriptions. For example, the average member of the critical group might be an individual worker who spends half of

his or her work days on-site and the other half inside a building, or the average member of the critical group might be the farmer who is involved in the daily operations of a working subsistence farm located within the contaminated zone. Each critical group, then, is defined for each scenario, and the average member, to which the dose estimates apply, is specified in the description tables.

3.7 EXPOSURE SCENARIOS FOR JPG DOSE ESTIMATES

The risk of adverse effects to human health from inhalation, ingestion, or external radiation from DU fragments depends on credible exposure scenarios from the DU source through the environment to human receptors. Several potential exposure scenarios were considered, and from these a subset was developed to simulate the most reasonable exposures of humans using the lands surrounding the DU firing at JPG. Two sets of scenarios are developed: (1) those in effect while institutional controls are in place (Section 3.7.1), and (2) those in effect if institutional controls fail (Section 3.7.2). Two radiation dose limits are also in effect for the types of scenarios: 25 mrem y^{-1} is imposed in Section 1403 of 10 *CFR* Part 20 when institutional controls are in place, whereas the dose limit is 100 mrem y^{-1} if institutional controls fail. These dose limits do not replace the ALARA concept, that is, that radiation exposure will be kept as low as reasonably achievable and will be no more than the specified dose limit. Potential exposure scenarios are listed in Table 6 (institutional controls in place) and Table 7 (institutional controls failed), and each is considered for inclusion in the set of scenarios selected for analysis.

3.7.1 Institutional Controls in Effect

Institutional controls are methods to restrict access to specific areas. Physical controls in place at JPG consist of 7 ft (2.1 m) high, chain-link fence topped with V-shaped three-strand barbed wire around the perimeter of the site north of the former firing line and locked swing gates on all roads providing access to the DU Impact Area. In addition to these physical controls, administrative access control will be maintained by U.S. Fish and Wildlife (FWS) personnel in charge of the Big Oaks NWR. Physical controls will minimize the amount of contact the general public has with JPG lands, whereas the administrative controls will provide the forum needed to address safety and health issues related to site use. The scenarios described below are consistent with this concept of institutional controls at JPG.

The main characteristics of the exposure scenarios when institutional controls are in place are that exposures are limited because site use and site access are limited. In these scenarios, one of the more plausible receptors is the FWS personnel who work access control points regularly. With limited access beyond the site boundary (i.e., the fence that begins north of the former firing line and encloses the north end of JPG), scenarios that account for periodic exposure were developed and are described below. These scenarios include periodic hunting of deer and/or turkey within the institutionally controlled area and then consuming these game animals, and periodic fishing with consumption of the fish. Hunting is currently allowed on-site twice each year, and a similar arrangement for fishing is not unreasonable. Exposure of hikers, bicyclists, bird watchers, and other participants in outdoor activities has also been described below. Also included are potential exposures for farmers and homeowners who live at the site boundary and are considered off-site.

Table 6. Potential Exposure Scenarios with Institutional Controls in Place^a

Scenario Number	Scenario Name	Description and Critical Group Identification	Exposure Pathways	Analyzed in DP?	Justification if not analyzed
1	On-site Worker	The critical group spends up to 4 days each month in the vicinity of the DU Impact Area for activities related to operation of the site.	<u>External exposure:</u> DU in soil. <u>Inhalation:</u> Resuspension of DU-containing dust. <u>Ingestion:</u> (1), (2) incidental ingestion of DU-containing soil; and (3) no pathways from drinking water, crops, or livestock.	Yes	
2	On-site Hunter	The critical group spends a limited amount of time on-site for hunting. Hunting period is two 1-week periods per year, and game consumed replaces all dietary meat each year. Hunting does not occur in the DU Impact Area. Game is either deer or turkey.	<u>Ingestion:</u> (1) Consumption (off-site) of game animals that feed in contaminated area is the only exposure pathway	Yes	
3	Off-site Fisherman	The critical group spends a limited amount of time off-site for fishing in Big Creek. Fishing period is 32 hours per month (4 days) for 3 months, or 12 days each year. Fish taken on-site will replace all dietary fish.	<u>Ingestion:</u> (1) Consumption (off-site) of fish obtained from water of Big Creek contaminated by (2) no pathways from drinking water, crops, or livestock.	Yes	

Table 6. Potential Exposure Scenarios with Institutional Controls in Place (Continued)

Scenario Number	Scenario Name	Description and Critical Group Identification	Exposure Pathways	Analyzed in DP?	Justification if not analyzed
4	Off-site Resident Farmer	The critical group is a family that lives on a farm at the institutional boundary of JPG. This farm is approximately 2.5 km (1.5 mi) from the DU Impact Area. Family raises all crops and livestock for consumption with minimal sources of commercial food products. Family lives near Big Creek, uses water from Big Creek for irrigation and drinks well water down-gradient of JPG. Location of farm is Node 13 in Figure 1 of Attachment 1.	<u>External exposure:</u> DU in soil deposited from irrigation with water from Big Creek. <u>Inhalation:</u> Resuspension of DU-containing dust. <u>Ingestion:</u> (1) Crops, meat, and milk from livestock raised on soils contaminated by irrigation; (2) fish from stream or pond contaminated by DU leaching through soil and transporting from JPG; (3) incidental ingestion of DU-contaminated soil; and (4) use of drinking water that contains DU from JPG.	Yes	
5	Off-site Boundary Recreationist	The critical group spends a limited amount of time at the JPG boundary but remains off-site. Activities could include hiking, camping, hunting, or other outdoor activities. Recreationists would not have access to JPG area under institutional control.	<u>Ingestion:</u> Consumption of game animals or fish that grazed, browsed, or lived in contaminated area at JPG; incidental ingestion of DU-containing soil deposited from irrigation; and no pathways from drinking water, crops, or livestock.	No	Scenarios 2 and 3 (Hunting and Fishing) are equivalent to this exposure scenario

Table 6. Potential Exposure Scenarios with Institutional Controls in Place (Continued)

Scenario Number	Scenario Name	Description and Critical Group Identification	Exposure Pathways	Analyzed in DP?	Justification if not analyzed
6	Off-site Boundary Recreationist (Hunter) ^b	The critical group spends a limited amount of time near the site boundary for hunting. Hunting period is two 1-week periods per year, and game consumed replaces all dietary meat each year. Game is either deer or turkey. Game assumed contaminated by grazing on-site and migrating off-site.	<u>Ingestion</u> : (1) Consumption (off-site) of game animals that grazed from contaminated area; and (2) no pathways from drinking water, crops, or livestock.	No	Exposure to this group already bounded by exposures evaluated in Scenario 2.
7	Off-site Part-time Resident	The critical group lives in a cabin or vacation home up to 50% of the year. All food is assumed uncontaminated and comes from off-site; drinking water from municipal source.	<u>External exposure</u> : DU in soil deposited by irrigation with water from Big Creek. <u>Inhalation</u> : Resuspension of DU-containing dust. <u>Ingestion</u> : Incidental ingestion of DU-contaminated soil deposited by irrigation.	No	Bounded by Scenario 4.

Table 6. Potential Exposure Scenarios with Institutional Controls in Place (Continued)

Scenario Number	Scenario Name	Description and Critical Group Identification	Exposure Pathways	Analyzed in DP?	Justification if not analyzed
8	Off-site Part-time Resident, Mod. 1	The critical group visits a home site periodically each year and lives in a cabin or vacation home up to 4 months each year. All food assumed uncontaminated and comes from off-site; drinking water from municipal source. Residents grow vegetables in small garden that is irrigated with water from a well at the site boundary or approximately 2.5 km (1.5 mi) from DU-contaminated area.	<u>External exposure:</u> DU in soil contaminated by irrigation with water from Big Creek. <u>Inhalation:</u> Resuspension of DU-containing dust. <u>Ingestion:</u> Incidental ingestion of DU-contaminated soil; and irrigated vegetable crops in season.	No	Bounded by Scenario 4, Table 7.
9	Off-site Industrial Worker	Critical group works indoors in a building at the site boundary. Drinking water supplied by a well that could be affected by contaminated zone leaching. Work ranges from office jobs to heavy industrial jobs. Scenario covers exposure to U.S. Fish and Wildlife Service personnel or other administrators.	<u>External exposure:</u> DU in soil deposited by irrigation with water from Big Creek. <u>Inhalation:</u> Resuspension of DU-containing dust. <u>Ingestion:</u> (1) Incidental ingestion of DU-contaminated soil deposited by irrigation; and (2) drinking water from well.	Yes	

Table 6. Potential Exposure Scenarios with Institutional Controls in Place (Continued)

Scenario Number	Scenario Name	Description and Critical Group Identification	Exposure Pathways	Analyzed in DP?	Justification if not analyzed
10	Off-site Industrial Worker	People who work indoors at the site boundary (e.g., in the cantonment area), JPG. Drinking water from well that is 5 mile from JPG. Work ranges from office jobs to heavy industrial jobs.	<u>External exposure</u> : DU in soil deposited by irrigation with water from Big Creek. <u>Inhalation</u> : Resuspension of DU-containing dust. <u>Ingestion</u> : (1) Incidental ingestion of DU-contaminated soil deposited by irrigation; and (2) consumption of DU-containing water from well.	No	Bounded by Scenario 9.
11	City Resident	People who live in Bedford, IN and use water originating from Big Creek.	<u>Ingestion</u> : (1) Consumption of drinking water-contaminated by soil eroded from the DU Impact Area	Yes	

^aRESRAD input and output data are available on CD upon request to the U.S. Army SBCCOM.

^bReplacement of meat with game follows Ferenbaugh et al. (2002).

Note: Dose limit is 25 mrem y⁻¹.

DU = depleted uranium.

JPG = Jefferson Proving Ground.

Table 7. Potential Exposure Scenarios Following Loss of Institutional Control^a

Scenario Number	Name	Description	Exposure Pathways	Analyzed in DP	Reason not analyzed
1	Resident Farmer, without irrigation ^b	Critical group is a family who moves onto site after institutional controls fail. They have their home on-site and raise crops and livestock for family consumption. This scenario represents the maximum likely exposure to the person outside the most, often tending the farm.	<u>External exposure:</u> DU in soil. <u>Inhalation:</u> DU-containing dust. <u>Ingestion:</u> (1) Crops, meat, and milk from livestock raised on DU-contaminated soil; (2) fish from stream or pond contaminated by DU leaching through soil; (3) incidental ingestion of DU-contaminated soil; and (4) drinking water that contains DU.	Yes	
2	Resident Farmer, with irrigation ^{b,cb}	Scenario is same as #1, but the crops require irrigation.	<u>External exposure:</u> DU in soil. <u>Inhalation:</u> DU-containing dust <u>Ingestion:</u> (1) Crops, meat, and milk from livestock raised on DU-contaminated soil; (2) fish from stream or pond contaminated by DU leaching through soil; (3) incidental ingestion of DU-contaminated soil; (4) drinking water that contains DU; and (5) crops, meat, and milk depend on contaminated irrigation water.	Yes	

Table 7. Potential Exposure Scenarios Following Loss of Institutional Control (Continued)

Scenario Number	Name	Description	Exposure Pathways	Analyzed in DP	Reason not analyzed
3	On-site Hunter	People who spend a limited amount of time on-site for hunting. Hunting period is two 1-week periods per year, and game consumed replaces 50% of dietary meat each year. Game is either deer or turkey. Assume hunting occurs in DU Impact Area.	<u>External exposure:</u> DU in soil. <u>Inhalation:</u> DU-containing dust. <u>Ingestion:</u> (1) Consumption (off-site) of game animals obtained from contaminated area; (2) incidental ingestion of DU-containing soil; and (3) no pathways from drinking water, crops, or livestock.	Yes	
4	On-site Fisherman	People who spend a limited amount of time on-site for fishing. Fishing period is 32 hours per month (4 days) for three months, or 12 days total. Fish taken on-site will replace all dietary fish. Assumes fishing occurs in DU Impact Area	<u>External exposure:</u> DU in soil. <u>Inhalation:</u> DU-containing dust <u>Ingestion:</u> (1) Consumption (off-site) of fish obtained from contaminated stream or pond; (2) incidental ingestion of DU-containing soil; and (3) no pathways from drinking water, crops, or livestock.	No	Exposure identical with Scenario 3 (Table 6). This scenario and Scenario 3 (Table 6) represent more likely exposures to DU than from farming in Scenario 1.
5	Domestic ^b	Critical group lives in houses within area formerly under access control and grows vegetables for home consumption in summers. Water from well located at DU-contaminated area boundary.	<u>External exposure:</u> DU in soil. <u>Inhalation:</u> DU-containing dust. <u>Ingestion:</u> Consumption of fish obtained from contaminated stream or pond; incidental ingestion of DU-containing soil; drinking water and vegetables; and no pathway from livestock.	Yes	

Table 7. Potential Exposure Scenarios Following Loss of Institutional Control (Continued)

Scenario Number	Name	Description	Exposure Pathways	Analyzed in DP	Reason not analyzed
6	Part-Time Domestic ^b	The critical group visits a home site periodically each year and lives in a cabin or vacation home up to 4 months each year. All food assumed uncontaminated and comes from off-site; drinking water from municipal source. Residents grow vegetables in small garden that is irrigated with water from a well at the site boundary or approximately 2.5 km (1.5 mi) from DU-contaminated area.	<u>External exposure:</u> DU in soil. <u>Inhalation:</u> DU-containing dust. <u>Ingestion:</u> Incidental ingestion of DU-contaminated soil; and irrigated vegetable crops in season.	Yes	

^aRESRAD input and output data are available on CD upon request to the U.S. Army SBCCOM.

^bScenario is unlikely because of significant risk of injury to farmer from unexploded ordnance.

^cIrrigation of farms in southern Indiana is rare (U.S. Department of Agriculture Stats.) but is included in this scenario for completeness.

Note: Dose limit is 100 mrem y⁻¹.

DP = Decommissioning Plan.

DU = depleted uranium.

The scenarios listed in Tables 6 and 7, while representative of a wide range of potential exposures, contain common pathways. The following scenarios from Table 6 were not included in the RESRAD simulations, and reasons for elimination are given. Scenario 5 was eliminated because doses from off-site recreationists are covered by Scenario 2 (hunters) and Scenario 3 (fisherman). Scenario 6 was eliminated because it is bounded by analysis of Scenario 2. Scenarios 7 and 8 were eliminated mainly because the two are variations of the same exposure scenario, with potentially larger exposure to receptors in Scenario 4. Scenario 10 was eliminated because Scenario 9 accounts for exposures from the same environmental pathways but at higher doses in Scenario 9. Scenario 12 was included to provide an estimate of population dose due to consumption of drinking water potentially contaminated by erosion of the DU Impact Area.

There are concerns about DU transport in the smoke that occurs during controlled burning at JPG and subsequent doses to receptors via this pathway. The RESRAD modeling program does not specifically address inhalation of DU-containing smoke as an environmental pathway. Nonetheless, such a pathway could be approximated via the inhaled dust pathway and altering the mass loading for foliar deposition, but at the cost of increasing uncertainty in the estimated doses. As a preface to such modifications and to evaluate if the added uncertainty was justified, exposure to radionuclides (including DU in smoke from fires) was reviewed. There is some evidence that DU and other natural and anthropogenic radionuclides could transport considerable distances and result in small doses to receptors as a result of physical disturbances (Kerekes et al. 2001; Royal Society 2002a, 2002b). Total radioactivity increased in smoke from fires related to battle (Royal Society 2002b), controlled burns, and wildfires (Williams et al. 1998; Johansen et al. 2001; Kraig et al. 2001a,b), but the increased radionuclide concentrations did not result in significant doses to receptors. For example, Kraig et al. (2001a,b) showed that estimated doses to firefighters at the scene of a fire that lasted several days was approximately 0.2 mrem, whereas to people away from the fire scene, the estimated dose was approximately 0.06 mrem. These small increases in doses to various receptors were dominated by naturally occurring radioactive materials such as U in soils and/or worldwide fallout (Kraig et al. 2001a; Kerekes et al. 2001; Royal Society 2002b). While transport by smoke is a possible mechanism of DU transport, the small increase in expected dose to humans and the uncertainty introduced from modifications of the modeling program do not justify including this pathway in the present dose assessment. Thus, doses from DU transported by smoke during fires was not evaluated.

Scenarios included for analysis while institutional controls are in place are: (1) on-site worker, (2) on-site hunter, (3) off-site fisherman, (4) off-site resident farmer, (5) off-site industrial worker and (6) off-site member of the population. Table 6 shows the potential exposures that could affect the critical group of each scenario and the environmental pathways by which this exposures could occur.

3.7.2 Loss of Institutional Controls

Loss of institutional control implies failure of physical and administrative access control to the JPG lands north of the firing line. Site characteristics are such that the land could be farmed, developed, or used as habitat for wildlife or to support outdoor activities similar to those permitted at JPG as discussed above. However, even though institutional controls are assumed to fail, removal of UXO scattered throughout the JPG lands is not assumed. Thus, estimating all risks involved with using the JPG lands must include potential exposure to DU fragments in soil and water as well as potential injury and death from UXO-related encounters. The former risks will be estimated in this report, but the latter are beyond the scope of this work and are not be assessed as part of this Decommissioning Plan.

Because of the presence of millions of UXO items and with no plans to remove the UXO from JPG lands north of the firing line, intense activities, such as farming or development for residential homes or industry, are not realistic land uses. However, farming and development are considered as potential DU

exposure pathways and are included in the tested scenarios. Transport of DU by groundwater, surface water, soil erosion, and uptake by plants and animals is similar to that discussed above when institutional controls are in place. The main difference in the scenarios considered if institutional controls fail, besides probable exposure to UXO, is the proximity to the DU Impact Area where farming, residential development, or recreational use can take place. The farming scenarios described below assume that a resident farmer lives all year in a house built on the DU Impact Area and supports a family on produce and livestock on-site. Part-time residential scenarios assume that residents live part of the year in houses built on the DU Impact Area and grow vegetables during the summer (4 months) for consumption at home. Recreational uses of the lands are similar to those listed above (Table 6) except that the DU Impact Area is accessible. Table 7 lists the scenarios, potential exposure pathways, and if the scenario is included in risk estimates, or if not, why the scenario was eliminated from the dose estimates.

Scenarios selected for analysis when institutional controls fail are listed in Table 7. All scenarios were included for RESRAD analysis because they represent potential exposure to humans under scenarios not included when institutional controls are in place. Resident farmers, without and with irrigated crops, were one such scenario and are analyzed as Scenarios 1 and 2, respectively (Table 7). The on-site hunter encounters more exposure pathways in the case of loss of institutional controls than in the case of effective institutional controls. Domestic residents and part-time residents (i.e., summer vacationers) were also included for further analysis (Scenarios 5 and 6, Table 7). These scenarios cover exposure by the same environmental pathways as in Table 6, but with different magnitudes from the source term.

Developing the entire list of scenarios, then screening the list for the unique cases, simplified the RESRAD modeling process considerably. In addition, the lower bound and upper bound of potential exposure were estimated for the two dose limits so that release of the JPG site for restricted use can be evaluated.

3.8 METHODOLOGY

In this section, the methodology is discussed. Sections 3.8.1 to 3.8.7 address RESRAD codes and applications, general and scenario-specific parameter values, and common properties. Sections 3.8.8 to 3.8.16 address potential receptors, while Sections 3.8.17 and 3.8.18 discuss data for ingestion pathways.

3.8.1 RESRAD Codes and Applications

The DOE program, RESRAD 6.1 (Yu et al. 2001) was used for assessment of on-site and off-site dose assessments. The program is flexible enough to accommodate site-specific information for many of the parameters required in an assessment. This flexibility is extremely important when diverse pathways and complex exposure routes need to be modeled. RESRAD was developed by DOE specifically to evaluate the risk of residual radioactive material in soils and water under different land uses. Earlier versions of RESRAD have been used in previous assessments at JPG (Ebinger and Hansen 1994, 1996a,b, and 1998). Finally, the present version of RESRAD has been developed to include widely accepted values of many default parameters (i.e., not site-specific values but values required to run the program) as discussed by Kennedy and Streng (1992), Beyeler et al. (1996, 1998), NRC (1998a), Meyer and Gee (1999), and Meyer and Taira (2001). Use of RESRAD was intended to support the decommissioning and license termination process at JPG by incorporating a widely accepted assessment program.

Off-site deposition of DU-containing soils eroded from the contaminated zone provides the source term for off-site exposure scenarios. Attachment 1 is an analysis of potential floodwater flow through Big Creek with use of surface water for irrigation on farms downstream and off-site. Floodwater generation was estimated for various return periods using meteorological data from stations near JPG and digital elevation maps of the JPG area. In addition, soil erosion information was derived from soil surveys of JPG (Nickell 1985) and previous erosion research.

RESRAD 6.1 simulates transport of DU (or other radionuclides) in soils to various crops and plants for use by a farmer and groundwater used for drinking. RESRAD also can account for external exposure of receptors (Figure 6). The program requires input concentrations of radionuclides in the soil of the affected area. The soil concentration of DU, or source term, is assumed to be uniformly distributed over a defined affected area and is diminished only by radioactive decay, leaching, wind and water erosion, and uptake from soils, water, and air. The leaching model depends on several soil properties, including permeability, texture, and the distribution coefficient between soluble (i.e., mobile) DU and insoluble DU that remains in the soil and is not leached. Groundwater flow depends on the permeability of the geologic strata through which it flows as well as the structure of the underlying bedrock. The depth through which the DU migrates depends, again, on the underlying geologic formations and the depth of the water table. In general, DU and other contaminants simulated with RESRAD move more quickly in saturated, porous materials that are relatively thin in depth, whereas transport is slowed when the materials are less porous, deeper, react with the contaminant, or a combination of these.

3.8.2 Parameter Values for Exposure Modeling

The RESRAD program requires values for several dozen parameters in order to simulate contaminant flow from the source through the unsaturated and saturated media to groundwater or surface water. A general set of default parameters is built into RESRAD (Yu et al. 2001; NRC 1998a) and is based on “average” agricultural characteristics reported in the technical literature, or recently, on accepted default values (e.g., NRC 1998a). Default values more specific to license termination and/or decommissioning, hereafter called the NUREG/CR-5512 default values, have been integrated into NRC guidance (Kennedy and Streng 1993; Beyeler et al. 1996; NRC 1998a). A comparison of the RESRAD and an NRC program, decontamination and decommissioning (D&D), is made in NRC (NRC 1998a), and the two sets of general default values are also compared. Default and site-specific input values for RESRAD simulations are given for each scenario tested as Attachment 2.

3.8.3 Parameter Values for RESRAD Simulations

A large array of values is entered into each RESRAD simulation; in order to distinguish between default values and site-specific values for each scenario that was tested, a data catalog was designed (Table 8).

Table 8. Default and Selected Values for Various Parameters Used in RESRAD Simulations

Parameter	Default Value	JPG Value	Reference
Radionuclide Concentrations and Transport Parameters			
Depleted Uranium ^a (pCi g ⁻¹)	0	94 or 225	
Basic Radiation Dose Limit (mrem y ⁻¹)	25	25 or 100	
Uranium Distribution Coefficient ^b	50	50	Yu et al. 2001; Sheppard and Thibault 1992
Contaminated Zone Parameters			
Contaminated Zone Area (m ²)	10,000	5×10^5 or 1.2×10^6	SEG 1996a
Contaminated Zone Thickness (m)	2	0.15	SEG 1996a; Ebinger et al. 1995
Length Parallel to Aquifer Flow (m)	100	100	
Depth of Cover (m)	0	0	
Bulk Density of Contaminated Zone (g cm ⁻³)	1.5	1.4	Saxton et al. 1986; Meyer and Gee 1999
Contaminated Zone Erosion Rate (m y ⁻¹)	0.001	.001	
Contaminated Zone Total Porosity	0.4	0.45	Saxton et al. 1986; Meyer and Gee 1999
Contaminated Zone Field Capacity	0.2	0.3	Saxton et al. 1986; Meyer and Gee 1999
Contaminated Zone Hydraulic Conductivity (m y ⁻¹)	30	30	Meyer and Gee 1999
Contaminated Zone b Parameter	5.3	5.3	
Evapotranspiration Coefficient	0.5	0.5	
Wind Speed (m s ⁻¹)	2	2	
Precipitation (m y ⁻¹)	1	1	
Irrigation (m y ⁻¹)	0.1	0.1 or 0	
Irrigation Mode	Overhead	Overhead	
Runoff Coefficient	0.2	0.2	
Watershed Area for Nearby Pond or Stream (m ²)	1×10^6	1×10^6	
Accuracy for Computations	0.001	.001	
Saturated Zone Parameters			
Bulk Density of Saturated Zone (g cm ⁻³)	1.5	1.5	
Saturated Zone Total Porosity	0.4	.4	
Saturated Zone Field Capacity	0.2	.2	
Saturated Zone Hydraulic Conductivity (m y ⁻¹)	100	100	
Saturated Zone Hydraulic Gradient	0.2	.2	
Saturated Zone b Parameter	5.3	5.3	
Water Table Drop Rate (m y ⁻¹)	0.001	.001	
Well Pump Intake Depth (m) below water table	10	10	
Model for Water Transport	Nondispersive	Nondispersive	
Well Pumping Rate (m ³ y ⁻¹)	250	250	
Unsaturated Zone Parameters^c			
Number of Zones	1	5 ^c	
Thickness (for each zone) [m]	4	0.3 (total thickness of 3.6 m for unsaturated zone)	Nickell 1985; SEC Donohue 1992

Table 8. Default and Selected Values for Various Parameters Used in RESRAD Simulations (Continued)

Parameter	Default Value	JPG Value	Reference
Bulk Density of Unsaturated Zone (g cm^{-3})	1.5	1.35	Saxton et al. 1986; Meyer and Gee 1999
Unsaturated Zone Total Porosity	0.4	.45	Saxton et al. 1986
Unsaturated Zone Effective Porosity	0.2	.3	Saxton et al. 1986
Unsaturated Zone Field Capacity	0.2	.3	Saxton et al. 1986
Unsaturated Zone Hydraulic Conductivity (m y^{-1})	10	30	Meyer and Gee 1999
Unsaturated Zone b Parameter	5.3	5.3	
<i>Occupancy, Inhalation, and Gamma Parameters</i>			
Inhalation Rate ($\text{m}^3 \text{y}^{-1}$)	8,400	8,400	Yu et al. 2001; Beyeler et al. 1998
Mass Loading for Inhalation (g m^{-3})	0.001	.001	
Exposure Duration (y)	30	30	
Inhalation Shielding Factor	0.4	.4	
External Gamma Shielding Factor	0.7	.7	
Indoor Time Fraction	0.5	.5	
Outdoor Time Fraction	0.25	.25	
Shape of Contaminated Zone	Circular	Circular	
<i>Ingestion Pathways, Dietary Data</i>			
Fruit, Vegetable, and Grain Consumption (kg y^{-1})	160	80	
Leafy Vegetable Consumption (kg y^{-1})	14	15 ± 6.0	Beyeler et al. 1998
Milk Consumption (L y^{-1})	92	78 ± 17.7	Beyeler et al. 1998
Meat and Poultry Consumption (kg y^{-1})	63	52 ± 7.4	Beyeler et al. 1998
Fish Consumption (kg y^{-1})	5.4	16 ± 7	Beyeler et al. 1998
Seafood Consumption (kg y^{-1})	0.9	0.9	
Soil Ingestion (g y^{-1})	36.5	36.5	
Drinking Water Intake (L y^{-1})	510	510	
<i>Contaminated Fraction</i>			
Drinking Water	1	1	
Livestock Water	1	1	
Irrigation Water	1	1	
Aquatic Food	0.5	1	
Plant Food	–1	1	
Meat	–1	1	
Milk	–1	1	
<i>Ingestion Pathways, Non-Dietary Data</i>			
Livestock Fodder Intake for Meat (kg d^{-1})	68	68	
Livestock Fodder Intake for Milk (kg d^{-1})	55	55	
Livestock Water Intake for Meat (L d^{-1})	50	50	Beyeler et al. 1998; also default
Livestock Water Intake for Milk (L d^{-1})	160	160	
Livestock Soil Ingestion (kg d^{-1})	0.5	0.5	
Mass Loading for Foliar Deposition (g m^{-3})	0.0001	0.0001	
Depth of Soil Mixing Layer (m)	0.15	0.15	
Root Depth (m)	0.9	0.9	
<i>Groundwater Use Fractions</i>			
Drinking Water	1	1	
Livestock Water	1	1	

Table 8. Default and Selected Values for Various Parameters Used in RESRAD Simulations (Continued)

Parameter	Default Value	JPG Value	Reference
Irrigation Water	1	1	
<i>Plant Transfer Factors</i>			
Wet Weight, Non-leafy Yield	0.7 kg m ⁻²	0.7 kg m ⁻²	
Wet Weight, Leafy Yield	1.5 kg m ⁻²	1.5 kg m ⁻²	
Wet Weight, Fodder Yield	1.1 kg m ⁻²	1.1 kg m ⁻²	
Translocation Factor, Non-Leafy	0.1 y	0.1 y	
Translocation Factor, Leafy and Fodder	1 y	1 y	
Weathering Removal Constant	20 y ⁻¹	20 y ⁻¹	
Wet Foliar Interception Fraction	0.25	0.25	
Dry Foliar Interception Fraction	0.25	0.25	

^aNominal isotopic composition of depleted uranium is from Schlieren (1992).

^bA separate distribution coefficient is required for the contaminated zone, each unsaturated zone, and the saturated zone.

^cProperties for each of the five horizons are entered in forms in Appendix A; data shown only for the first horizon in Table 8.

Note: See Attachment 2 for a complete listing of parameters.

JPG = Jefferson Proving Ground.

RESRAD = Residual Radioactivity.

Site-specific values are indicated in the center column of the catalog form, and each set of site-specific values will be discussed. The complete set of data catalog forms is included as Attachment 2.

The basic configuration for the RESRAD simulations consists of a contaminated zone of 0.15 m (15 cm) in thickness, an unsaturated zone of five soil horizons and based on site soil surveys (Nickell 1985), and an underlying saturated zone. The DU source term is included in the 0.15-m-thick contaminated zone, and the entire concentration is evenly distributed across the contaminated zone area. The various hydrologic, physical, and chemical parameters common to each exposure scenario are discussed below, then parameter values specific to each scenario are listed. In this way, the unique characteristics of the different scenarios can be illustrated separately from the common parameters.

3.8.4 Common Properties: Contaminated Zone

The contaminated zone is a single soil horizon of 0.15-m thickness that is of the same physical and chemical properties as the surface horizon of the local soils. The permeability of the contaminated zone soil is determined by the bulk density of the soil; soil porosity, field capacity, and effective porosity; the hydraulic conductivity; and infiltration of precipitation or irrigation that is affected by runoff, evapotranspiration, and precipitation amount. These values were estimated from soil texture using a hydraulic property calculator (Saxton et al. 1986). Hydraulic conductivity values from the calculator tend to be about a factor of 10 greater than the RESRAD default value of 10 m y⁻¹. Meyer and Gee (1999) report a distribution of conductivities that ranges from 9.8 × 10⁻² m y⁻¹ to 980 m y⁻¹ with mean of 29.4 m y⁻¹ and standard deviation of 69 m y⁻¹ for silt loam soils. This distribution was used to estimate the conductivities of the various soil horizons including the contaminated zone. Soil total porosity, field capacity, effective porosity, and bulk density from the calculator were similar to measure values of Meyer and Gee (1999). From these data, the average conductivity of 30 m y⁻¹ was used with bulk density of 1.4 g cm⁻³, total porosity of 0.45, effective porosity of 0.3, and field capacity of 0.3. Annual precipitation was estimated from JPG records and other sources (see Attachment 1), and default values for evapotranspiration, runoff, and applied irrigation were used because no better data from JPG were available. The default value for a watershed to support a pond on the contaminated zone soils was used since a pond the size of the contaminated zone is reasonable based on poor drainage and ponding on the soils at JPG.

Transport of DU through the soil is controlled mainly by the distribution coefficient, K_d , in addition to the permeability of the soil. There are several values in the literature that are applicable to uranium transport in soils, and selecting values without measurements from JPG soils is uncertain (e.g., Baes and Sharp 1983; Clapp and Hornberger 1978; Isherwood 1981; Sheppard and Thibault 1990; Yu et al. 2001). However, the various studies can be used to bound a value selected for these simulations, then the selected value can be subjected to sensitivity and/or uncertainty analyses to estimate the effect on risk estimates of varying the K_d s. Experimental values of K_d s are subject to various chemical properties such as pH and ionic strength of solutions within which the values are measured. The 15 cm of soil that makes up the contaminated zone is reportedly slightly acidic, potentially about pH 5 to 6 (Nickell 1985). Eliminating K_d values that apply outside this range gives several values that range from about 10 to over 200. K_d s less than 100 are the more commonly measured (see Yu et al. 2001, Table E-7; Sheppard and Thibault 1990), and the mean is near the RESRAD default value of 50. With no additional data from JPG soils, the default K_d was used and sensitivity analysis covering a factor of 10 (K_d from 5 to 500) was implemented (Figure 7). From previous studies, the K_d value is the parameter that most affects dose estimates after variation in the source concentration.

3.8.5 Common Properties: Unsaturated Zone (Soil Zone)

The predominant soil type within the DU Impact Area is Cobbsfork silt loam, although a variety of soils occur near where the Big Creek dissects the loess-over-glacial till landscape (Nickell 1985). All soils within the DU Impact Area are represented by similar chemical and physical properties that include poor to somewhat poorly drained soils (i.e., soils that are wet and could pond); textures of mainly silt loam and clay loam; the presence of a fragic horizon or a thick soil horizon that is very impermeable to water; and all are relatively non-erosive except on steeper slopes leading to the Big Creek drainage. Cobbsfork silt loam will be considered the soil of the contaminated zone for the RESRAD simulations. A typical soil profile description is shown in Table 9, and this general description is the basis for the unsaturated, uncontaminated zone that separates the contaminated zone from the aquifer. Values for the top horizon were entered into the data catalog (Table 8 and Appendix A), and the values in Table 9 for each of the other horizons were input but not shown in Table 8. The thickness of the unsaturated zone was estimated from the average depth to groundwater from wells located in the DU Impact Area (SEC Donohue 1992). The average of 9 wells was 3.6 m (± 1.8 m). The thickness of the lowest soil horizon (i.e., unsaturated zone 5 in Table 2-1) was adjusted to give a total unsaturated zone thickness of 3.6 m.

Table 9. Profile Description and Characteristics of Cobbsfork Silt Loam

Horizon Depth (cm)	Texture (USDA)	Field Capacity	Saturation	Saturated Hydraulic Conductivity (m y^{-1}) ^a	Bulk Density (g cm^{-3}) ^b
0–30	Silt loam	0.3	0.45 to 0.5	148 to 290	1.33 to 1.37
30–68	Silt loam	0.3	0.45 to 0.5	148 to 290	1.33 to 1.46
68–127	Silt loam	0.3	0.45 to 0.5	52 to 148	1.33 to 1.37
127–195	Silt loam	0.3	0.45 to 0.5	52 to 148	1.33 to 1.37
195–203	Silt loam	0.32	0.52	46 to 52	1.27 to 1.33

^aRange from Nickell (1985) and Saxton et al. 1986. Values increase with increasing sand. Estimated average value for Cobbsfork silt loam shown. Meyer and Gee (1999) show a log normal distribution with mean of 29.4 m y^{-1} , standard deviation of 69 m y^{-1} , and range from 0.098 m y^{-1} to 980 m y^{-1} .

^bCalculated from texture using Saxton et al. 1986; Meyer and Gee (1999) bulk density estimates also similar.

Source: Data from Nickell (1985) and estimates from Saxton et al. (1986).

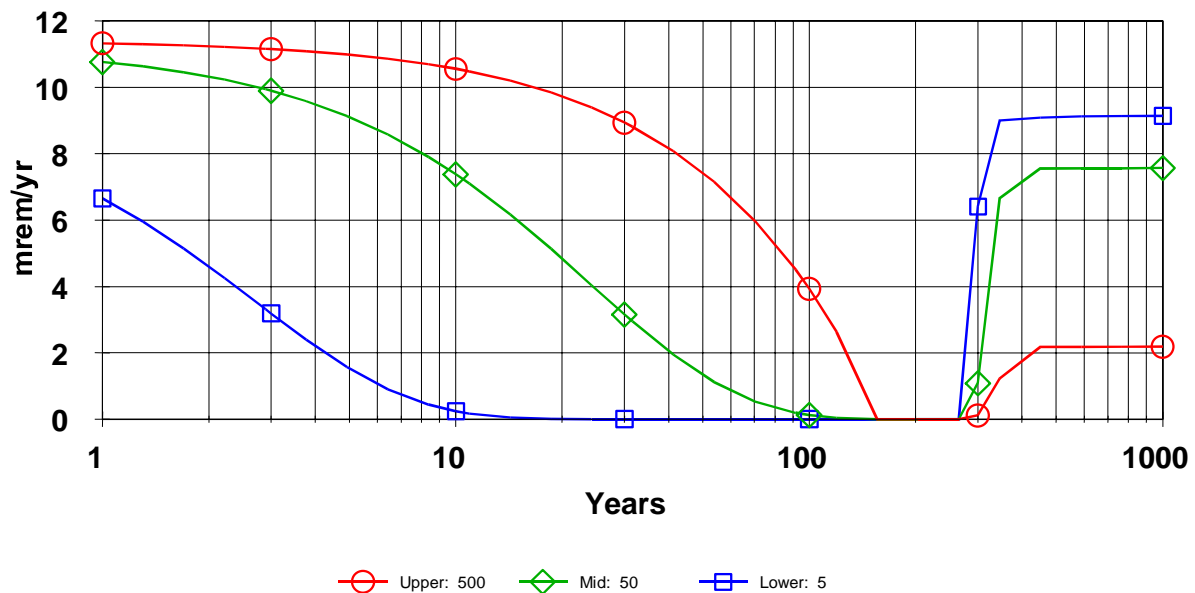
cm = centimeter.

g = gram.

m = meter.

USDA = U.S. Department of Agriculture.

**DOSE: U-238, All Pathways Summed With SA on U-238 Contaminated Zone
Distribution Coef.**



NIC1sen.RAD 05/02/2002 12:56 Includes All Pathways

**Figure 7. Results of RESRAD Sensitivity Analysis on the K_d of the Contaminated Zone Soil
(Values for K_d varied between 5 and 500.)**

3.8.6 Common Properties: Saturated Zone

Default values were used for the saturated zone since there were no site-specific data that could be used in place of defaults. The exception was the K_d value, which was estimated from literature values at 50 and varied by a factor of 10 in sensitivity tests. Table 2-1 (Attachment 2) lists the parameter values for those properties that are common throughout the RESRAD analyses. Scenario-Specific Parameters

The scenarios discussed above require different parameter values than the common properties listed in the last section. These parameters are scenario dependent and, thus, change to reflect the relevant exposure assessment. The scenario-dependent parameters are discussed here for each scenario, first for the simulations that evaluate exposures when institutional controls are in place, then for the simulations that evaluate exposures after loss of institutional control.

3.8.7 On-Site Worker

The average member of the critical group for this scenario spends the equivalent of 4 days each month involved in outdoor activities on the border of or within the DU Impact Area of JPG (Scenario 1, Table 6). Exposure pathways include external exposure, dust inhalation, and incidental soil ingestion, and no contribution from food or water produced on-site. Parameters of importance to this scenario are mainly the occupancy, inhalation, and gamma parameters of Table 8 and in Attachment 2 (Table 2-1, Table 2-2). Default parameters for the inhalation rate and mass loading of dust for inhalation were used because they were reasonable for moderate activity outdoors. Work hours spent indoors were approximately 0.2 yr, and the 4 days per month spent near the DU Impact Area was approximately 0.05 yr. Default soil ingestion was used since there are no data or other indications of potential to increase soil ingestion significantly. Table 2-2 (Attachment 2) shows input data for this scenario.

3.8.8 On-site Hunters

Two versions of this scenario are evaluated: the first for the case of effective institutional controls (Scenario 2, Table 6) and the second for the case of failed institutional controls (Scenario 3, Table 7). In each case, the average member of the critical group spends eight hours per day for up to two weeks each year (approximately 0.01 yr) hunting game that fed within the DU Impact Area of JPG and replaces up to 50% of dietary meat with turkey or deer hunted at JPG. In the first case, the hunter does not enter the DU Impact Area and receives exposure only through the meat ingestion pathway. In the second case, the hunter enters the DU Impact Area and is exposed to external radiation from soil, and DU-containing dust can be inhaled. Ingestion of DU is through meat consumption and soil ingestion, but consumption of potentially contaminated drinking water was not included. Occupancy, inhalation, and gamma parameters were default values except for indoor and outdoor times. Ingestion pathways included soil ingestion at a default value of 36.5 g y^{-1} and up to half of the meat consumed came from contaminated sources. Human consumption of contaminated drinking water was not part of the scenario, but it was assumed that the hunted deer only drank from contaminated sources, and contaminated water was used to grow the fodder for the deer. Consumption of vegetables, fruits, and grains grown on the contaminated site was not included in this scenario, neither was consumption of fish or dairy products produced on-site. Table 2-3 (Attachment 2) shows input data for the loss of institutional control version of this scenario.

3.8.9 Off-Site Fisherman

The average member of the critical group for this scenario spends up to four days for three months each year fishing in Big Creek downstream of the access-controlled area of JPG and replaces all dietary fish with fish caught at JPG (Scenario 3, Table 7). Concentration of uranium in surface water was estimated

using uranium concentration in soil, erosion rate and surface water flow rate modeled in Attachment 1 for Node 13. Dose was estimated using

$$D_{\text{fish}} = C_{\text{W,DU}} * \text{BCF} * \text{CR} * \text{DCF} \quad (1)$$

Where D_{fish} is the dose from fish consumption (mrem y^{-1}), BCF is the concentration factor for U-238 in fish (10 L kg^{-1} ; Yu et al, 2001), CR is the rate at which humans consume fish (15 kg y^{-1} ; Beyeler, 1998), and DCF is the dose conversion factor for ingestion of U-238 (Yu et al, 2001), and $C_{\text{W,DU}}$ is the concentration of DU in stream water after it erodes from the DU Impact Area (pCi/g) and is estimated from

$$C_{\text{W,DU}} = C_{\text{sed}} / K_d \quad (2)$$

Where C_{sed} is the concentration of DU in the sediment eroded from the DU impact area (pCi g^{-1}) and K_d is the distribution coefficient ($50 \text{ cm}^3 \text{ g}^{-1}$; Yu et al., 2001). C_{sed} is the estimated amount of DU in the sediment eroded from the DU impact area each year (pCi y^{-1}) and is estimated by

$$C_{\text{sed}} = C_{\text{erode}} / \text{Sed} \quad (3)$$

where C_{erode} is the amount of DU eroding from the Impact Area (pCi y^{-1}) and Sed is the total amount of sediment at Node 13 ($28,830 \text{ metric ton}$ or $2.88 \times 10^{10} \text{ g y}^{-1}$; Attachment 1, Fig. 1, Table 1) outside the JPG boundary. The Sed value was taken as the two-year return period as this value should more closely approximate the average sediment yield in Big Creek. C_{erode} is estimated from the fraction of the Big Creek watershed (90 km^2 ; Attachment 1, Fig. 1, Table 1) covered by the DU Impact area ($5 \times 10^5 \text{ m}^2$, or 0.5 km^2); the value of the fraction is 5.6×10^{-3} . Thus,

$$C_{\text{erode}} = 5.6 \times 10^{-3} * \text{Sed} * 225 \text{ pCi g}^{-1} \quad (4)$$

and $C_{\text{sed}} = 1.25 \text{ pCi g}^{-1}$, and $C_{\text{W,DU}} = 2 \times 10^{-2} \text{ pCi mL}^{-1}$. Thus, the dose to humans consuming about 15 kg of fish from Big Creek each year is approximately $8 \times 10^{-1} \text{ mrem y}^{-1}$. Values used in these calculations are shown in Table 2-4.

3.8.10 Off-Site Resident Farmer

The critical group is a family that lives on a farm at the institutional boundary of JPG. This farm is approximately 2.5 km (1.5 mi) from the DU Impact Area (Node 13; Attachment 1, Fig. 1). The family raises all crops and livestock for consumption with minimal sources from commercial food products. The family lives near Big Creek, uses water from Big Creek for irrigation, and drinks well water down-gradient of JPG. Soil contamination for the farm was assumed to be sediment deposited from Big Creek floods, thus the source of DU for the farm is the sediment eroded from the DU Impact Area and its estimated concentration is 1.25 pCi g^{-1} (see section 3.8.9). Water contamination is the DU that dissolves into Big Creek from the eroded sediment, and is $2 \times 10^{-2} \text{ pCi l}^{-1}$ as in Section 3.8.9. Using these inputs and all available pathways in RESRAD v. 6.1, doses to farmers at this site were estimated. Table 2-5 shows the input values for these estimates.

3.8.11 Off-Site Industrial Worker

The average member of the critical group for this scenario works in a building at the JPG boundary and spends work time indoors (Scenario 9, Table 6). No site access is allowed in this scenario, but the building water supply is derived from a well that is near the building which is near the DU Impact Area. Thus, the exposure pathway that exists for this scenario is from drinking water.

3.8.12 City Resident

The average member of the critical group for this Scenario (Scenario 11, Table 6) is a user of surface water located at the nearest municipal water take-up point downstream of the JPG. This point is located at Bedford, IN on the East Fork White River. Concentration of uranium in surface water is derived from the concentration of uranium in soil in the DU Impact Area and the estimate of erosion rate of soil. Dose was estimated using hand calculation as the product of concentration of uranium in surface water, water ingestion rate and dose conversion factor. Table 2-4 shows relevant values used in these calculations. The water concentration is estimated as in Section 3.8.9, using the amount of DU in sediments and water in Big Creek, then using the estimated volume flow of the East Fork of the White River ($3.74 \times 10^9 \text{ m}^3 \text{ y}^{-1}$; <http://waterdata.usgs.gov/nwis/qwdata>, Accessed 6/14/2002). Using Equations 2 and 3, the concentration of DU in water is approximately 9.6 pCi m^3 , and if water consumption is 510 L y^{-1} (or $0.51 \text{ m}^3 \text{ y}^{-1}$) and the DCF is as listed in Table 2-4, the dose to a city resident using White River water as drinking water is approximately $1.3 \times 10^{-3} \text{ mrem y}^{-1}$. If Big Creek water is used at Node 13 as drinking water, the resulting dose is slightly larger, $2.7 \times 10^{-3} \text{ mrem y}^{-1}$.

3.8.13 Resident Farmer, no Irrigation

This scenario occurs only after loss of institutional control to the area of the contaminated zone. The average member of the critical group for this scenario farms year-round on a location centered on the contaminated zone (Scenario 1, Table 7), and replaces up to all vegetables, meat, poultry, dairy products, and fish with farm-raised products. The resident farmer is exposed to external radiation from soil, and DU-containing dust can be inhaled. Ingestion of DU is through consumption of vegetables, beef and poultry, milk and other dairy products, and fish, and consumption of potentially contaminated drinking water. Occupancy, inhalation, and gamma parameters were default values. Table 2-7 shows input data for this scenario.

3.8.14 Resident Farmer, Irrigation Allowed

This scenario also occurs only after loss of institutional control to the area of the contaminated zone. The average member of the critical group for this scenario farms year-round on a location centered on the contaminated zone, uses irrigation from streams or ponds that contain water from the contaminated zone, and replaces up to all vegetables, meat, poultry, dairy products, and fish with farm-raised products (Scenario 2, Table 7). The resident farmer is exposed to external radiation from soil, and DU-containing dust can be inhaled. Ingestion of DU is through consumption of vegetables, beef and poultry, milk and other dairy products, and fish, and consumption of potentially contaminated drinking water. Occupancy, inhalation, and gamma parameters were default values. Table 2-8 shows input data for this scenario.

3.8.15 Domestic Resident

This scenario also occurs only after loss of institutional control to the area of the contaminated zone. The average member of the critical group for this scenario lives year-round on a location built on the contaminated zone, uses irrigation from streams or ponds that contain water from the contaminated zone, replaces up to 33 % of vegetables with products raised in a home garden in the summers and 33% of fish consumed annually with fish from contaminated waters, but does not produce farm-raised meat, poultry, or dairy products (Scenario 5, Table 7). The domestic resident is exposed to external radiation from soil, and DU-containing dust can be inhaled. Ingestion of DU is through consumption of vegetables and fish, but not beef or poultry, milk, or other dairy products. Occupancy, inhalation, and gamma parameters were default values. Table 2-9 shows input data for this scenario.

3.8.16 Part-Time Domestic Resident

This scenario is similar to the previous one except that the resident and average member of the critical group only live in the house for 4 months each year, in the summer. The part-time resident raises all of the vegetables used for the 4-month period (0.33 y) in the garden located in the contaminated zone and replaces all fish consumed with fish caught in contaminated waters at JPG. The part-time resident is exposed to external radiation from soil, and DU-containing dust can be inhaled. Ingestion of DU is through consumption of vegetables and fish, but not beef or poultry, milk, or other dairy products (Scenario 6, Table 7). Occupancy, inhalation, and gamma parameters were default values. Table 2-10 shows input data for this scenario.

3.8.17 Ingestion Pathways and Human Dietary Data

Several compilations of data on the amount of food consumed by humans show relatively large variation. The larger values were selected to ensure conservatism in the risk estimates from exposure to DU via food pathways. Where distributions of values were given (e.g., Beyeler et al. 1998), the standard deviation or variance was used to vary the parameter value, or the distribution was used in simulations if variation of the parameter affected the dose estimate by more than about 10%. Where values of RESRAD parameters were not given and could not be derived without uncertainty, the RESRAD defaults were used.

3.8.18 Ingestion Pathways and non-Human Dietary Data

As with human dietary data, the more conservative values for needed parameters were selected from compilations of data or RESRAD defaults were used. The values chosen were subjected to sensitivity and/or uncertainty analyses to test which of the parameter values affected the dose estimates the most. Default values for plant transfer factors were used throughout the analyses as variation in these factors produced changes of less than 1% in predicted doses to humans. Contaminated fractions of drinking water, water for irrigation and livestock, aquatic, plant, beef, and milk products were selected as “1” if a pathway was allowed in a scenario or “0” if that pathway was not allowed.

3.9 SENSITIVITY AND UNCERTAINTY ANALYSES

The output of the RESRAD program depends on the various values of the input parameters used; thus, it is important to evaluate which of the input parameters most affects the output doses. The resident farmer scenario (Table 7, Scenarios 1 and 2) evaluated doses to the farmer through all of the environmental pathways available to RESRAD for these simulations and provided the initial evaluation of model sensitivity. RESRAD was run as a deterministic model for these evaluations, that is, set parameter values were used and varied, then the dose to humans was monitored. The changes in the parameters that caused the largest magnitude of change in estimated doses were considered sensitive parameters. Conversely, those parameters that could be changed with little to no effect on the output doses were considered insensitive parameters. Changes in parameter values of a factor of 5 to 10 that caused changes in output of 10% or greater were considered highly sensitive parameters; those parameters that resulted in 1 to 10% change in the output doses were considered medium-sensitivity parameters, and parameters of low sensitivity caused less than 1% difference in output doses. Table 10 shows the parameters evaluated and the results of the sensitivity analysis.

Table 10. Results of Sensitivity Analyses for Several RESRAD Parameters

High Sensitivity	Medium Sensitivity	Low Sensitivity
K _d of Contaminated Zone	K _d of Unsaturated and Saturated Zones	Porosity and hydraulic conductivities of Contaminated and Unsaturated Zones
Mass Loading for Inhalation (g m ⁻³)	Bulk Density of All Zones	Porosities of all Zones
Drinking Water Intake Rate (l d ⁻¹)	Hydraulic Conductivity of Saturated Zone Indoor and Outdoor fractions Inhalation Rate of Receptor Soil Ingestion Rate Food Ingestion Parameters (milk intake rate, amount of fruit, vegetables, and grain ingested, etc.)	

Three parameters were most sensitive in the analysis, the distribution coefficient of the contaminated zone soil, the mass loading value for inhalation pathways, and the drinking water ingested by the receptors. Food ingestion rates were also considered of high interest to the dose results, although these values proved to be less sensitive than the distribution coefficient, mass loading, and drinking water intake. Most of the parameters tested were of medium sensitivity. These parameters included the distribution coefficients of the saturated and unsaturated zones; the physical parameters of the unsaturated and saturated zones, including hydraulic conductivities, bulk densities, and porosities of the various layers; the fraction of time spent indoors and out; and the food ingestion rates. Of low sensitivity were additional hydrologic properties in the unsaturated zones. Scenarios that included multiple pathways for exposure of receptors, like the farming scenarios, naturally resulted in larger doses received by the receptors. Conversely, those scenarios with relatively uncomplicated exposure pathways resulted in smaller doses.

Uncertainty analysis is a means by which the distribution of output values is estimated, that is, the degree of error in estimated values is established. Uncertainty analysis uses distributions of parameter values for each parameter in the analysis. A value for each parameter is selected at random from the distribution, the dose is calculated for that set of parameter values, then the process begins again. Value selection can either be completely at random from the distribution, or selected at random from individual segments of the entire distribution. The latter method is the Latin hypercube sampling method (McKay et al. 1979; Inman et al. 1981; Helton and Inman 1982) and forces sampling of the tails of the parameter distribution. This method tends to increase the average value in some cases and ensures that the largest and smallest values of a distribution are included in the analysis. Three hundred iterations of the model are run during an uncertainty analysis, so each distribution is sampled 300 times (Yu et al. 1993; Yu et al. 2001, Appendix M; Kamboj et al. 2000; LePoire et al. 2000). In this way, a set of 300 output values is derived that can be described statistically.

Uncertainty analysis using all the parameters in the RESRAD model for each scenario is a large task that is extremely inefficient because the contributions of all the parameters would be included for each estimated dose for each scenario. However, the set of parameters included in the analysis can be refined using the information from the sensitivity analysis described above. Using the sensitivity information, the distribution coefficient for the contaminated zone, the drinking water intake rate, and the mass loading for inhalation were used in the uncertainty analysis. Also included were the food ingestion factors for the scenarios that included food pathways. This reduced list of variables for the uncertainty analysis was a much smaller set of calculations to perform, and interpretation of the resulting data was a less daunting task.

Selecting probability distributions for the parameters used for the uncertainty analysis was relatively difficult and is the source of error itself in the analysis. Clearly, variation in source term concentrations, area of the contaminated zone, and depth of the contamination are directly related to the input values: an increase in one results in a proportional increase in the estimated dose. Instead of including distributions for the soil concentration of DU, contaminated zone size, and depth of the contamination, two sets of values for the source term (94 pCi g^{-1} and 225 pCi g^{-1}) were used, two contaminated zone areas were used, and the depth of contamination was set at 15 cm based on previous data (see also discussions above on source term and contaminated zone area). No site-specific data were available for the other parameters chosen for the uncertainty analysis even though these parameters were the main source of variation in the estimated doses. Instead, various literature sources were used to estimate probability distributions for these and variables, and the food ingestion rates. The probability distributions, the values used for the uncertainty analyses, and the source of the values are given in the tables of Attachment 2, whereas results are discussed in the next section.

In addition to the sensitivity to values of parameters, the sensitivity of dose to the presence of trace contaminants in DU was investigated. Dose due to the presence of Pu-238/239/240 and Tc-99 was estimated for the on-site residential farmer scenario. Concentration levels of plutonium and technetium in DU armor were those reported in Section 4.0, 5 and 540 pCi/g for Pu-238/239/240 and Tc-99, respectively.

3.10 RESRAD RESULTS

The parameter distributions used for the uncertainty analysis require some discussion since all were estimated from the literature and not from site-specific measurements. The distribution coefficient, K_d , for the contaminated zone was estimated at 50 milliliters per gram (mL/g) using various literature values (Yu et al. 1993; Yu et al. 2001), and the sensitivity analysis showed that smaller values of K_d affected the dose more than values larger than 50 (Figure 6). To capture the larger changes in doses from smaller values of K_d , a triangular distribution was selected for K_d . The minimum value was 5, the maximum was 60, and the median was 50. Thus, more values between 5 and 50 were selected in the uncertainty iterations than between 50 and 60. Literature and site-specific data on mass loading for inhalation, or the amount of DU-containing dust in the air, were sparse. The distribution selected follows that reported by Beyeler et al. (1998) and is a uniform distribution between 0.0001 and 0.001. The upper value is the largest reported in the literature (Baes and Sharp 1993; Meyer and Gee 1999; Yu et al. 2001) and is slightly larger than the maximum value reported by Beyeler et al. (1998). The uniform distribution ensured that all values in the distribution were selected with equal probability.

Drinking water intake rates varied over a relatively wide range (Yu et al. 1993; Beyeler et al. 1998). Several values near 440 L y^{-1} were suggested, and the largest reasonable rate listed was about 660 L y^{-1} . With a wide distribution of values, the uniform distribution was a conservative choice, and the distribution was constructed between 440 and 660 L y^{-1} . The food ingestion rates were also variable depending on the source. Lognormal distributions of values were chosen from Beyeler et al. (1998) as the most likely.

Results of the probabilistic dose estimates are presented in Table 11 for all scenarios. The average largest dose and standard deviation of that dose were estimated in the uncertainty analyses and presented in the results tables along with the range of the largest dose values predicted. Inhalation and external exposure were the major dose components in all scenarios, and they were the dominant components of scenarios that were not affected by drinking water or food ingestion pathways that depended on water use. Figure 8 shows the estimated dose with time for the On-Site Worker and illustrates the dominance of the external exposure and inhalation pathways. Figure 9 shows the dose with time for the On-Site Hunter and the effects of ingestion of game.

Table 11. Results from RESRAD Simulations of all Scenarios

Scenario (Table)	Concentration (pCi g ⁻¹)	Average Dose (mrem y ⁻¹)	S.D.	Minimum Dose (mrem y ⁻¹)	Maximum Dose (mrem y ⁻¹)	Time at Average Dose (y)
1 (6)	94	1.2	0.3	0.7	1.7	0
	225	2.9	0.7	1.6	4.1	0
2 (6)	94	0.8	0.03	0.7	0.9	0
	225	2.0	0.08	1.7	2.2	0
3 (6)	225 ^a	8.1 x 10 ⁻¹				
4 (6)	1.25 ^b	0.2	0.04	0.1	0.3	0
9 (6)	94	2.7	0.5	1.9	3.5	0
	225	6.4	1.1	4.5	8.4	0
11 (6)	225 ^a	1.3 x 10 ⁻³		(Bedford, IN)		
	225 ^a	2.7 x 10 ⁻³		(Big Creek)		
1 (7)	94	15.5	2.8	10.0	20.5	1000 ^c
	225	37.0	6.8	24.5	49.1	1000 ^c
	0.3 ^d	0.1	0.01	0.07	0.2	0
	0.03 ^e	0.05	0.02	8 x 10 ⁻³	0.09	0
2 (7)	94	15.4	2.7	10.4	20.4	1000 ^c
	225	26.8	6.7	23.6	48.9	1000 ^c
3 (7)	94	1.49	0.3	0.9	2.1	0
	225	3.6	0.8	2.2	4.9	0
5 (7)	94	14.4	2.6	9.58	19.4	1000 ^c
	225	34.5	6.3	22.9	46.4	1000 ^c
6 (7)	94	10.7	1.4	7.5	14.7	1000 ^c
	225	35.3	3.4	17.9	35.3	1000 ^c

^aDose to human receptor calculated by hand, and no probabilistic results were possible with this program.

^b Dose to human receptor calculated by RESRAD v. 6.1, and soil concentration estimated to be 1.25 pCi g-1 from erosion and sediment modeling (Attachment 1).

^cDose at 1,000 years due to fish and plant ingestion pathways.

^d dose from Tc-99 residue in DU alloy.

^e dose from Pu-239 residue in DU alloy.

Note: Values are from uncertainty analyses.

S.D. = Standard Deviation.

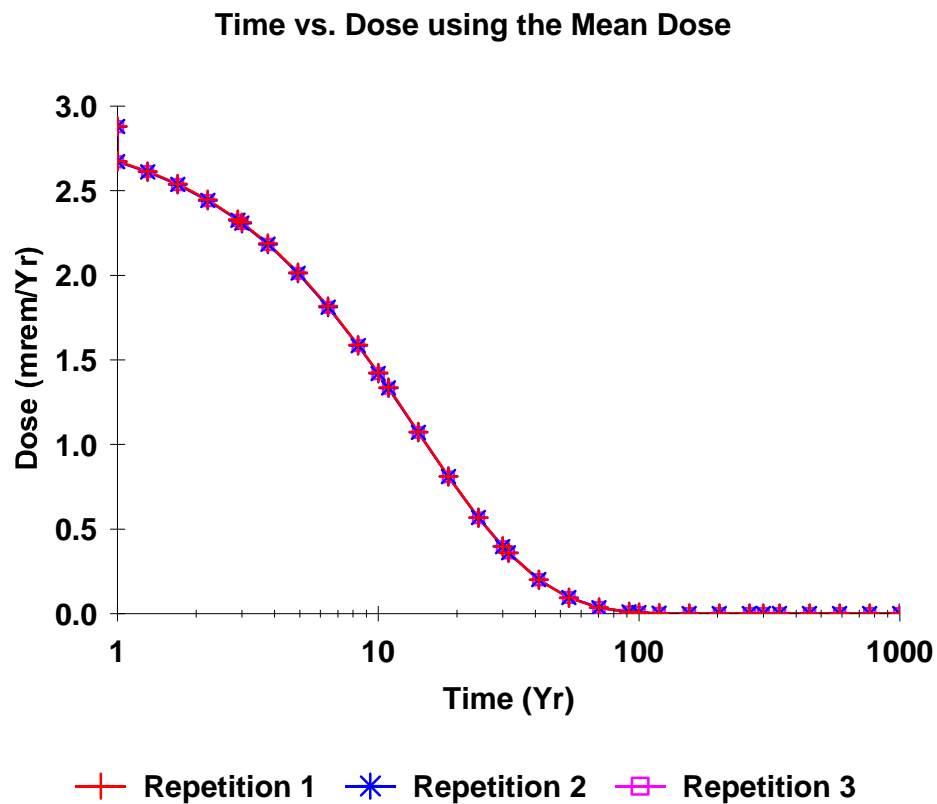


Figure 8. Plot of predicted dose vs. time for On-Site Worker (Scenario 1, Table 6). Data shown for soil concentration of 225 pCi g-1 and three repetitions of probabilistic risk assessment in RESRAD 6.1. Estimated dose prior to year 100 from external and inhalation pathways.

Time vs. Dose using the Mean Dose

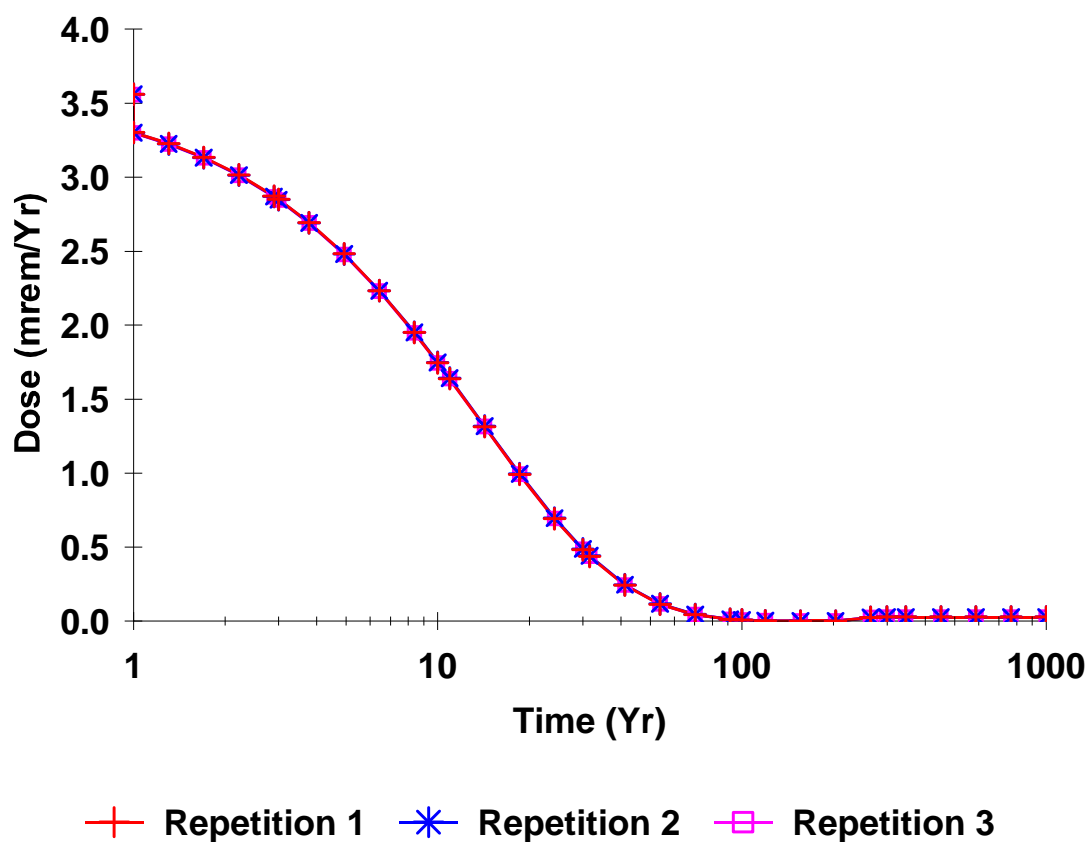


Figure 9. Plot of predicted dose vs. time for On-Site Hunter (Scenario 3, Table 7). Data shown for soil concentration of 225 pCi g-1 and three repetitions of probabilistic risk assessment in RESRAD 6.1. Estimated dose prior to year 100 from external and inhalation pathways, with little to no contribution from ingested meat.

The dose occurs after the initial dose from inhalation and external exposure because of the time to transport the DU 100 m from the contaminated zone.

Figure 10 shows dose with time for the Resident Farmer after loss of institutional controls and reflects the dose due to all food ingestion pathways after the DU transports to surface water sources used for raising fish, irrigating crops and livestock, and drinking water. The increased importance of the external and inhalation pathways is due to the significant amount of time spent outside in the contaminated area where the farm is located. The overall dose increased compared to doses shown in Table 11 and Figures 8 and 9, due to the increased amount of DU in food items and from external and inhalation exposure increases. Dose to the resident farmer from trace concentrations of Tc-99 and Pu-239 are included in Table 11 as additions to Scenario 1(7). Data for this analysis was taken from Section 4; the concentration for Tc-99 was 0.3 pCi g^{-1} -soil, and for Pu-239 was 0.03 pCi g^{-1} -soil. The resulting doses were small compared to overall doses from DU.

Exposure of off-site farmers while institutional controls are in place (Scenario 4, Table 6) indicates that minimal exposure (e.g., about 1 mrem y^{-1}) occurs based on erosion of soil containing DU to Big Creek and use of water from Big Creek for irrigation at the off-site location Floodwater and sediment yield modeling (Attachment 1) support the idea of only slightly increased exposure to DU eroded from the contaminated zone. The estimate of the DU concentration in the sediment delivered to this location takes the sediment yield (Table 12, Attachment 1) from the contaminated zone area, then the amount of DU is calculated based on the soil concentration used in RESRAD simulations (either 94 pCi g^{-1} or 225 pCi g^{-1}). The total activity of DU is then divided by the estimated flow rate of Big Creek to calculate the concentration of uranium in Big Creek exiting JPG. The concentration of uranium in soil at off-site location was estimated based on use of water from Big Creek for irrigation and partitioning of the uranium onto the soil.

3.11 EFFECTS OF UNCERTAINTY IN PARAMETER VALUES

Many of the parameters used for the RESRAD modeling and the flood and sediment modeling were determined from literature values of these parameters, not from actual field measurements. There are clear changes in predicted doses if DU concentrations change or if the size of the contaminated zone changes; these possibilities were controlled by adjusting the model simulations for high or low concentrations from large or small, contaminated zones. While field measurements and empirical estimates of the parameter values are ideal, the imminent personnel safety hazard due to the presence of UXO, the ecological impact of obtaining additional field measurements and the cost to produce such a catalog is prohibitive and extremely time-intensive. However, use of the best values for various parameters based on measurements from other locations, then using distributions of those values for sensitive parameters in the models, can account for some of the uncertainty in estimated doses.

The dose calculations presented above represent use of as much site-specific information as possible coupled with literature values for similar parameters in determining the values and distributions of the values used in the models. Presentation of the distributions of the estimated doses also provides an evaluation of variation in the estimates and allows for better decisions on if the site can be released for restricted use.

Time vs. Dose using the Mean Dose

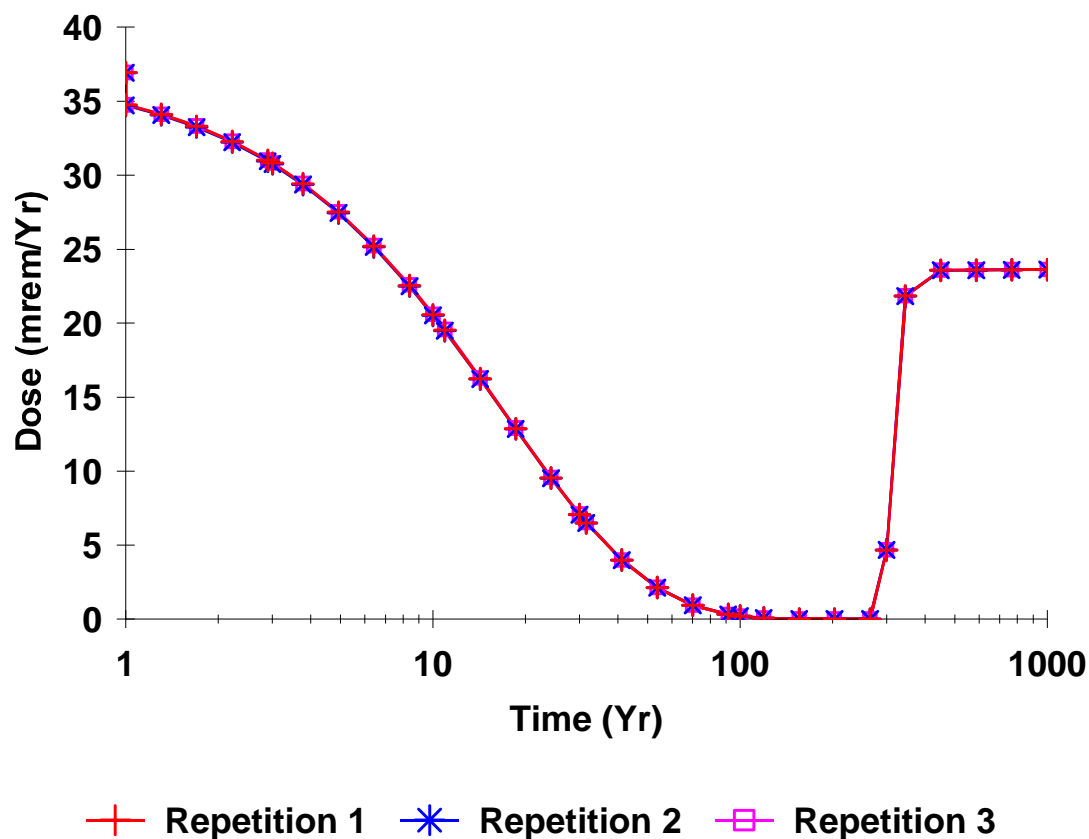


Figure 10. Plot of expected dose vs. time to Resident Farmer (Scenario 1, Table 7). Estimated dose prior to year 100 due to external and inhalation pathways. Estimated dose after year 300 due to ingestion of fish, vegetables, meat, dairy products, and drinking water contaminated with DU transported from the DU Impact Area. Data shown for soil concentration of 225 pCi g-1 and three repetitions of probabilistic risk assessment in RESRAD 6.1.

4.0 CONCLUSIONS

The doses to average members of specific critical groups using JPG lands were predicted with the RESRAD program for a variety of exposure scenarios. The means, standard deviations, and ranges for all predictions were less than the dose limits for restricted release when institutional controls were in place (25 mrem y^{-1}) or when institutional controls failed (100 mrem y^{-1}). These dose estimates are based on a combination of site-specific parameter values used in RESRAD, values and their distributions estimated from literature on the parameters, and default values that are required to run the program.

Sensitivity analyses on many of the parameters indicate that variations in K_d of the contaminated zone soils, mass loading for inhalation, and drinking water intake rates caused changes of 10% or more in the predicted doses, whereas variations in other parameters do not result in significant changes in the predicted doses. Means, standard deviations, and ranges of estimated doses were calculated by probabilistic methods integrated into the RESRAD program, and none of the values exceeds the dose limits for any of the scenarios tested.

Overall, the results suggest that exposures to residual DU at JPG are well below the dose limits of 25 mrem y^{-1} or 100 mrem y^{-1} established for restricted release when institutional controls are in place or after loss of institutional control, respectively, as specified in 10 *CFR* 20, Section 1403. However, since the restricted release guidelines are specific to radiological doses to human receptors, these dose estimates do not address the potential effects of chemical toxicity to humans exposed to DU through these scenarios, the radiological toxicity of DU to ecosystem receptors, or the risk of injury or death to the members of the critical groups due to UXO accidents. Risk of adverse health effects in humans due to radiation from DU is low, based on the analyses in this report, and is potentially the smallest of the various risk factors regarding JPG site use.

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